Electric Power Systems

AUTOMATIC POWER SYSTEM CONTROL

MIR PUBLISHERS
MOSCOW

ИЗДАТЕЛЬСТВО
МИР

Electric Power Systems

Automatic Power System Control

General Editor:
Prof. V.A. VENIKOV, D.Sc. (Tech.)

Translated from the Russian
by V. M. Matskovsky

MIR PUBLISHERS
MOSCOW

Богданов В. А., Веников В. А., Лугинский Я. Н., Черня Г. А.

ЭЛЕКТРИЧЕСКИЕ СИСТЕМЫ

Автоматизированные системы управления
режимами энергосистем

Под редакцией докт. техн. наук, проф. В. А. Веникова

Высшая школа, Москва

First published 1982
Revised from the 1979 Russian edition

The Greek Alphabet

Α α	Alpha	Ι ι	Iota	Ρ ρ	Rho
Β β	Beta	Κ κ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	Τ τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
Ε ε	Epsilon	Ν ν	Nu	Φ φ	Phi
Ζ ζ	Zeta	Ξ ξ	Xi	Χ χ	Chi
Η η	Eta	Ο ο	Omicron	Ψ ψ	Psi
Θ θ ϑ	Theta	Π π	Pi	Ω ω	Omega

На английском языке

© Издательство «Высшая школа», 1979
© English translation, Mir Publishers, 1982

Contents

Preface 9

Introduction 11

I.1. Basic Concepts and Definitions 11
I.2. An Outline of Trends in the Power Industry 12
I.3. Management and Control of Energy Systems and Usage of Energy Resources 14
I.4. Large Energy Systems and the GOELRO Plan 16
I.5. Ecology and Power Industry 17
I.6. Development of the Power Industry as a Large System and Its Advantages 18
I.7. Power System Automatic Control and Quality of Supply . . . 21
I.8. Dispatch Control and Its Tasks 24
Review Questions 27

Chapter 1

Large Energy Systems. Theory of Management and Control 28

1.1. General 28
1.2. Management and Control of Pan-energy System Expansion and Operation 33
1.3. Power Industry Cybernetics 36
1.4. Conditions of the Consumption of Electrical Energy 43
1.5. Control Systems 47
Review Questions 54

Chapter 2

Power System Management and Control 56

2.1. General 56
2.2. Primary, Secondary and Tertiary Regulation 58
2.3. Automatic Control of Power System in Normal State of Operation 61
2.4. Economic Dispatch 72

2.5. Control of Normal Operation of Power Systems with Free Tie-Line Power Flows 75
2.6. Control of Normal Operation of Power Systems with Controllable Tie-line Power Flows 92
2.7. Voltage Control in Networks of Interconnected Power Systems 99
2.8. Power System Management and Control in the Soviet Union and Its Future Trends 103
2.9. Organization of Dispatch Control in the Soviet Union 116
Review Questions 122

Chapter 3

Data Display Facilities of Automated Dispatch Control Systems 124

3.1. Visual Displays. Means and Methods 124
3.2. CRT Input-Output Display Units 130
3.3. Data Display Systems at Control Centres 150
Review Questions 157

Chapter 4

Computers in Power System Control 158

4.1. General 158
4.2. Computing Centers of Power Dispatching Offices 160
4.3. Real-time Computer Systems 166
4.4. Computing Equipment at Power Stations and Substations . . . 180
4.5. System Effectiveness at Plants and Ways to Improve It . . . 189
Review Questions 190

Chapter 5

Collection and Transmission of Information in ADCS 192

5.1. Communication Channels. General 192
5.2. Multichannel Pulse-Coded Modulation Telecontrol Devices . . . 203
5.3. Information Accuracy 221
5.4. Data Transmission Systems 223
5.5. Input, Storage and Processing of Teleinformation 238
Review Questions 252

Chapter 6

Analog Computers and Their Application in Power Industry 253

6.1. General 253
6.2. Building Blocks of Analog, Hybrid Computers and Hybrid Computing Systems 261
6.3. Application of Multipurpose Analog and Hybrid Computers in Power Industry 279
6.4. Special-Purpose Analog and Hybrid Computing Systems Used in Power Systems and Interconnections 292
Review Questions 307

Chapter 7

Use of Digital Computers in Dispatch Control of Power Systems . . . 309

7.1. General 309
7.2. Information: Its Formats, Input, Output and Storage 316
7.3. Data Processing. Central Processing Unit 322
7.4. Computer Speed 335
7.5. Channels. Operating System. Data Management 341
7.6. Mini-Computers 356
Review Questions 360

Chapter 8

Emergency Control of Power Systems 361

8.1. General 361
8.2. Principles of Automatic Emergency Control 362
8.3. Elimination of Emergency Conditions 364
8.4. Structure of Automatic Emergency Control 371
8.5. Emergency Situations and Requirements for Emergency Control 374
8.6. Effect of Emergency Control on Power System Operation under Emergency Conditions 385
8.7. Criteria and Algorithms of Transients Control Methods 418
Review Questions 439

Bibliography 440

Index 441

From the book:

An energy system ..... is a complex of installations that provide consumers with heat, light and power. It may also be referred to as a general energy system, or as an energy supply system. Energy systems feature a hierarchical stucture whose respective levels are responsible for supply of energy to the entire country, to an area, a large load centre, or to an individual industrial undertaking...

Preface

There are many organizations in this country which deal with the design of management control systems in great variety. Such systems are vitally important in power industry since it uses energy production and consumption processes of complex and continuous nature, and consists of hundreds of big utilities spread over a vast territory.

This book, which is the seventh volume of the treatise "Electric Power Systems", will provide a text for students taking basic courses on the design and operation of management control systems in power industry, and will also serve as a useful reference for engineers dealing with the associated problems. Such specialists, who may be called power system cyberneticists, must familiarize themselves with various subject-matters, including major power industry production processes and modern methods of their management and control, and this book covers a great deal of the topics concerned.

Thus the audience for this book will include relatively broad sections of readers, and the material offered is divided into eight chapters concentrically, as in the case of the other volumes of the treatise. For instance, Introduction deals with general concepts, which are treated in more detail in Chapters 1 and 2. On the other hand, basic problems associated with power system management and control are dealt with in Chapters 1 and 2 and are then elaborated in Chapters 3-7.

Chapters 1 and 2 cover the specific features of modern power systems treated as large and rapidly developing systems of cybernetic nature. Here an attempt is made to formulate major tasks to be tackled in controlling the operating conditions of interconnected power systems and to describe technico-economic aspects concerned with automated means for power system management and control.

Chapters 3-7 deal with various control equipments, including digital and analog computers, telecontrol and communications facilities designed to gather, transmit and display control data. Chapter 8

gives a thorough discussion of systems engineering and cybernetic aspects of emergency control schemes used to control operating conditions of modern power systems.

The bibliography at the end of the book will lead the reader to certain additional sources.

For the first time the book tries to discuss the material concerning power system management and control problems jointly and systematically, and the authors beg to be excused for any errors that might have crept in inadvertently. Suggestions for improving the book will be highly welcome.

The authors also wish to thank Jacob N. Luginsky for tireless and painstaking scientific revision of the English version of the book's Introduction and Chapters 1, 2, 3, 4, 6.4 and 8.

Authors

Introduction

1.1. Basic Concepts and Definitions

This book surveys the applications of various cybernetic and mathematical modelling techniques for certain problems concerned with the control of operating conditions for large power systems and, in particular, with the dispatch control of such systems. Before speaking of the management and control of the present-day power industry, it is necessary to give a more detailed explanation for some of the basic concepts dealt with in the six previous books comprising the treatise "Electric Power Systems".

An energy system, as may be recalled, is a complex of installations that provide consumers with heat, light and power. It may also be referred to as a general energy system, or as an energy supply system. Energy systems feature a hierarchical structure whose respective levels are responsible for supply of energy to the entire country, to an area, a large load centre, or to an individual industrial undertaking. The nation-wide level is represented by a *united power grid*. An *interconnected* energy system is associated with an area comprising several districts, and a *regional* energy system, with one region only.

An energy system is called *autonomous* when no links to connect it with other systems are available.

Associated with energy systems are all processes involving production, conversion, distribution and usage of all types of energy resources, including the initial stage of resources extraction and the final stage of energy use. Thus energy systems constitute the basis for the development of the power industry as a whole, and the problems that apply to the control of such systems, called sometimes *large energy systems* (LESs) are the subjects being taught herein.

The LESs include such constituents as power systems which in turn comprise electricity and heat supply systems. Other constituents of the LESs are oil, gas and coal supply systems and nuclear power systems, which are being developed. The individual energy supply systems are growing into an integrated super-system which

may be called *an interbranch fuel-and-energy complex*. This is mainly due to the fact that different forms of energy and different types of energy resources are being utilized within the framework of the national economy as interchangeable items. The units of the present course depicting the dispatch control of power systems must be treated, therefore, in connection with the description of those subsystems which are part of a large energy system and which interact with one another.

An energy system and the fuel-and-energy complex have many similar features. The importance of both the entities to the national economy chiefly consists in the fact that the country's key branches of industry are using the fuel-and-energy complex as their foundation and depend on the conditions thereof. In leading countries the development of the fuel-and-energy complex requires approximately one third of the total capital investment and from 15 to 20 per cent of the total manpower.

Individual energy supply systems incorporated in a large energy system may also be treated as large systems.

I.2. An Outline of Trends in the Power Industry

There are three aspects concerned with expansion and operation of energy systems. Having rather distinct features, they seem to encounter some difficulties both in the present-day situation and in the future. The first aspect—*technico-economic*—concerns the improvement of existing equipment and design of new equipment which could offer economies. The second aspect—*socio-demographic*—deals with the factors by which the power industry tends to influence social and political processes, including the siting of industrial enterprises and industrial distribution of working population on the nation-wide scale. The third aspect—*ecological*—concerns the biosphere, namely, the environmental effects caused by the power industry.

When we try to treat a power system as a means providing the national economy with all forms of energy, it is feasible to introduce the term country's fuel and energy supplies by which an entity is meant that incorporates a set of power installations which are linked together to cover the total consumers' load. Thus the term country's fuel and energy supplies can be used as an equivalent of the term fuel-and-energy complex.

Any energy system should be characterized by an *energy balance* which is defined as the ratio of energy generated to energy consumed, with energy losses being taken into account. Here, they are considered in time, territorial and industrial terms provided that the optimal transfer of all forms of energy and energy resources is ensured from stages of their extraction, processing, conversion and transportation to stages of their distribution, storage and use. The

energy balance is a vital characteristic of the continuously growing fuel-and-energy complex whose main components and links constitute an energy system.

The growth of the power industry influences the social progress which is related to the amount of energy supplied per unit of equipment. This quantity may be defined as the amount of energy which is utilized by machines, devices and appliances substituting for human labor. The fact that our century sees the advent of a new scientific discipline—electric automation—is due to the increased amount of energy available to industry and especially to the increased production of electrical energy and the improved techniques of its usage. The early development work in this field was concerned with special-purpose cybernetic machines (robots or manipulators) used to supersede hard manual labour. Recent investigations are aimed at the development of such devices which could be substituted for many types of noncreative mental work. Thus, the conditions under which both manual labour and mental work are armed with energy favour the application of cybernetic methods.

We may say, therefore, that the availability of energy for all kinds of human activities, including the energy necessary for home uses, is an important characteristic of social development. It determines and reflects not only the economic but also, to a certain extent, the cultural level of that development.

A large energy system is characterized by the following specific features:

(1) An indivisible material ensemble of energy systems whose integrity is determined by internal links and by the products interchangeability in subsystems and separate components.

(2) Products versatility in and importance to the national economy (especially electrical energy and liquid fuel), which involves a great number of external links.

(3) Its active influence upon the development and distribution of productive forces.

(4) Continuity in time for most processes connected with production and utilization of energy. This requires that energy and fuel users be incorporated in the system structure, the system operating conditions be maintained through the use of efficient control means, and supply of fuel be ensured on adequate and operational basis.

(5) Prevention of separate selection of the efficiency and parameters for the individual components, and links without the framework of their proposed usage in the system; significant importance of perspective planning and designing large energy systems as a single entity.

(6) Complex structures of systems because of their large size which results from the fact that they are formed as unified nation-wide systems or systems belonging to a group of adjacent countries.

Energy system structures can be differentiated by the types of energy sources utilized by the systems.

Physico-technical considerations are applicable when treating energy systems as large ones. In this case, attention should be focused on the investigation of the nature of the material links observed in electrical, gas- and oil-supply networks. On the other hand, economic approach can be employed in the case where the material connections are mainly described in terms of the purely information-oriented indicators. The physico-technical approach is used most advantageously in solving problems concerned with the operational control of systems production processes, while the economic approach successfully handles the problems associated with the management and control of systems growth and expansion.

It is important to stress that physico-technical and economic parameters of energy systems are closely interrelated. An energy system has cybernetic features, which means that deep-lying feedback paths exist in it. This requires that all subsystems incorporated in a given system be treated as a single complex. The working and control functions being performed in an energy system on a continuous basis combine the activities of human operators and those of control devices included in the feedback control loop. There is a certain relationship between energy system operation control and energy system planning control.

The treatment of a large energy system as a global system reveals itself chiefly in social aspects. Indeed, the supply of energy differs considerably from one country to another, and this accounts for a tremendous gap between their levels of economic and cultural development. It is known that 50 per cent of the earth's total population living in developing countries consume not more than 7 per cent of the energy obtained from all world energy sources available. The consumption of electrical energy in 43 countries having 30 per cent of the earth's total population amounts to 90 per cent of the world's electrical energy consumption, while the remaining countries with 70 per cent of the earth's population consume the remaining 10 per cent. Assessed in terms of per-capita energy consumption, the difference is represented by the ratio of 1:50 for all energy sources and by the ratio of 1:1000 for electrical energy (for example, 15 000 kW h per capita in Norway and 15 kW h per capita in some African countries).

I.3. Management and Control of Energy Systems and Usage of Energy Resources

The purpose-oriented and optimizing effects of a large man-made system upon an energy system constitutes the core of energy system management and control. The control tasks involving all temporal

and territorial factors of the power industry are critical in terms of its improvement and expansion. Energy system management and control has the objective of obtaining such a performance level which most nearly approach the criteria set down for effectiveness. This type of management and control utilizing cybernetic methods provides conditions under which the control actions, when explicitly determined and influenced by the environment, make it possible to achieve the given goals on an optimum basis. In this connection, two fruitful approaches to management and control are as follows: system optimization, a technique used to decide on the viable solution in a defined set of possible solutions concerning further development; and optimization completion, a technique used to carry out the solution found by system optimization. The sequence of steps in which effective management and control actions are achieved will be:

(1) choice of optimum rates and proportions concerning the development of the fuel-and-energy complex embracing the united power grid and its subsystems;

(2) employment of modern equipment components which could ensure scientific and technological progress in the power industry;

(3) use of the entire national material and manpower resources in the most efficient manner, existing conditions being taken into consideration.

The end-product obtained from an energy system is the *net energy* by which is meant the energy delivered to users after the processing, conversion, transportation and storage of required energy resources to cover the users' requirement.

The performance of an energy system may be characterized by an extent to which the available energy resources are being utilized. The latter comprise the natural sources and stores of different forms of energy, both detected and evaluated, which can be utilized on a large scale. Energy resources differ in this respect from natural stores of energy such as solar, geothermal, wind sources, and energy contained in seas and oceans. The major types of energy resources utilized in the modern world are fuels comprising coal, oil, natural gas, peat and combustible shale, water power, wood, fissile materials, and, partially, wind and tidal power. They may be grouped as follows: *renewable resources*, comprising water and wind power, direct solar radiation, and tidal power, and *nonrenewable resources* such as coal, oil, natural gas, and combustible shale.

As to the extent of exploration, the reserves of minerals can be classified into the following three groups: A—actual reserves; B—probable reserves; and C—projected reserves. It is necessary to differentiate between projected (usable) energy resources and their economic potential. The projected reserves also include such minerals whose extraction is unlikely to be practicable under the existing

conditions. The concept of equivalent fuel provides the basis of comparison for different types of energy resources and their effectiveness.

The projected fuel reserves of the world (coal, gas, peat, and combustible shale) amount to 11 651 $\times$ 10^9 tons, 54.5 per cent being available in the Soviet Union. The world's extractable reserves amount to 3.11 $\times$ 10^9 tons, 55 per cent being available in the Soviet Union. Water reserves, estimated to be equivalent to 7 500 $\times$ $\times$ 10^9 kW h per year, are available; this figure is 1.5 times the amount of electrical energy generated in 1970 by all electric stations of the world. Commercially usable water reserves of the Soviet Union would yield more than 1 700 $\times$ 10^9 kW h per year. Energy systems utilize two types of fuel such as energy-producing fuel used by electric stations and large boiler installations to produce electrical and thermal energy; and commercial fuel used by industrial installations, including furnaces and ovens, and by coking process.

The usage of energy resources may be estimated in terms of the coefficient of extraction of the potential resources. It is defined by the ratio of the total amount of a given energy resource being drawn upon under existing technological conditions to the potential reserve of that resource. For the purpose, use is also made of the coefficient of utilization of energy resources by energy-consuming processes in various industries and the national economy as a whole. The coefficient of utilization is the product of the efficiencies of individual processes comprising all stages that begin at the extraction of a given energy resource and terminate in the use of the produced energy.

We may conclude, therefore, that large energy systems involve different types of energy resources, i.e. those energy carriers that cover existing and will cover further needs of the national economy.

Any energy system is associated with the extraction, preparation, processing, conversion, transportation, storage and use of energy carriers and also the recovery of all secondary energy resources. These processes, which greatly influence energy system operational and planning problems, are the subjects presented in the general theoretical course in energy systems (power engineering), which involves a number of disciplines concerning specific subsystems and their associated problems.

I.4. Large Energy Systems and the GOELRO * Plan

The second half of the twentieth century saw the advent of energy systems, which have been growing in recent decades into large systems. However, from the historical point of view, the treatment of the power industry as the entity comprising large systems stems

* The State Plan for Electrification of Russia adapted by the Soviet Government in 1920.

from the GOELRO plan. It was at that time (the year 1920) that the world's first integrated plan was drawn up to provide for the economic development of the country on the basis of electrification. At the same time, the GOELRO plan advanced the idea of unifying the country's fuel and energy supplies and their tying up with the national economy as a whole.

Thus the management of the present-day power industry in the Soviet Union is based on the integrated political and economic principles, including the planned nature of the national economy and a systems analysis approach to management and control problems; the combined branch-wise and territorial types of management and the hierarchical principle of energy system control; and the consideration of the environmental effects caused by the power industry. Pollution control equipment is finding growing application in the modern world at a fast rate and requires considerable capital investment. Pollution control problems must be solved, therefore, by the power engineers who develop and operate energy systems and their components, such as electric stations, substations and transmission lines.

1.5. Ecology and Power Industry

The modern approach to pollution control requires that all remedies be organic components of power engineering installations and not auxiliary means added to them after their construction. This is due to increasing overall installed capacity (8 to 10 $\times$ 10^9 kW per year) of various power engineering installations of the world, which consume annually not less than 6 to 7 $\times$ 10^9 tons of equivalent coal (7 000 kcal/kg) to produce different forms of energy. Indeed, the action exerted by the power industry on the environment is commensurate in terms of power with life events, both geophysical and geological, that could change the face of the earth.

The overall energy consumption in the world is continuously increasing. It is reasonable, therefore, to suppose that the energy produced by world power installations would reach a value commensurate with the energy received by the earth from the sun. Though at present, the former is several hundredth per cent of the latter, it, nevertheless, exerts a considerable effect on the climate, especially in areas with intense electricity supply. In such areas, the biosphere is subject to thermal pollution. Since existing energy-producing plant has a comparatively low efficiency of energy conversion (25 to 30 per cent for major installations and 8 to 10 per cent for small autonomous installations), thermal losses due to heating the water, soil and air in the environment are tremendously high.

Sharp environmental hazards may be due to the improper development and design of hydro power plant reservoirs, when an attempt

is made to solve hydro power engineering problems only. The most dangerous air pollutants are the ash and flue gas (nitrogen oxide, sulfur dioxide and others). All these harmful environmental effects can be minimized (and could be eliminated in a more distant future) by using the suitable approach to the development of the individual power installations and integrated energy systems. This means that the power industry should be treated primarily as a large system having firm ties with many types of human activity and influencing the environment.

The power engineers dealing with the development and operation of dispatch-controlled large energy systems would concern themselves more and more with optimization problems and exercise control over them not only on the basis of existing economic criteria (including minimal cost of energy obtained) but also on the basis of the conditions in which "pure" energy would be obtained through the use of production processes with a minimal danger of polluting the environment.

The floor areas and building volumes of structures required for present-day power industry are increasing, which tends to result in certain ecological problems. The proper layout and arrangement of these buildings make it possible to drastically reduce floor and volume space requirements. In 1900, for example, volume space requirement for an electric station was 50 m^3/kW but decreased down to 6 m^3/kW 50 years later. At present, the employment of closed-type switchgear filled with insulating gases allows the above characteristic to be reduced to several tenths of cubic metre per kilowatt. Further improvements in this field are promising, and better environmental control could thus be achieved.

The expansion and growth of the power industry and other industries as well would cause ultimately the advent of new production processes in which all wastes could be eliminated or kept at a minimum. In such circumstances, very stringent environmental demands would be satisfied.

1.6. Development of the Power Industry as a Large System and Its Advantages

The electric part of an energy system, which includes electric stations involved in parallel operation, transmission lines, substations and consumers, is called the *power system* (PS). The characteristic features of PS's are the availability of the common reserve capacity and of centralized operational dispatch control bodies used to coordinate the operation of stations, substations and networks in accordance with a unified load schedule. In a broad sense, we shall conform to the term power system to include heat- and power stations and their distribution networks. In this case by a

power system is meant a system that provides on a centralized basis electricity and heat for industrial and domestic uses.

It is possible to describe the electric part of an energy system in terms of practical power-industry applications. This allows a power system to be treated as a complex including electric components in which different electric and electromechanical phenomena occur which are connected, in turn, with certain mechanical and thermomechanical phenomena existing in turbines, boilers and pipelines. The PS's are very advantageous for the growth of the power industry for the following reasons: certain external factors, including those connected with system siting and availability of standby equipment, tend to weaken their limiting effects on system parameters, with the result that the power rating of stations and units can be increased on the optimum economy basis:

the reliability of electricity supply is increased on account of a more flexible handling of the reserves of the entire system and a decrease in the total requisite reserve capacity;

the total load peak is decreased due to staggering the daily load peaks in individual areas, which results in a decrease in the desired generating capacity of the interconnected system;

there exist conditions in which generating stations and units of various types can be operated in a more effective way: for instance, the most economical high-power condensing electric stations are used to provide the base load, while the peak load is handled by a hydro-electric plant and special-purpose, pumped-storage and gas-turbine electric stations;

energy resources of various types, including fuel for which long-haul transportations are economically impracticable, can be utilized with higher efficiency on account of trunk transmission lines available to large power systems;

cutting down of the volume of fuel transportation, and the large-scale utilization of hydro power resources which are considerably distant from the consumers;

the ability of individual power systems to join together so as to cover the entire country's territory or its considerable part.

Figure I.1 shows the interconnections of the Soviet Union joined together to form the United Power Grid (UPG).

There are the following major characteristics of power systems: installed capacity; interconnections with other systems; generating mix; load flow density; and configuration.

As to their installed capacity, power systems can be broken down into three basic groups of the following ratings: above 5×10^6 kW; 1 to 5×10^6 kW; and below 1×10^6 kW. In the systems belonging to the second and third groups large units and stations may be used on a limited basis. The effectiveness of utilization of energy resources and installed capacity decreases with decreasing system size.

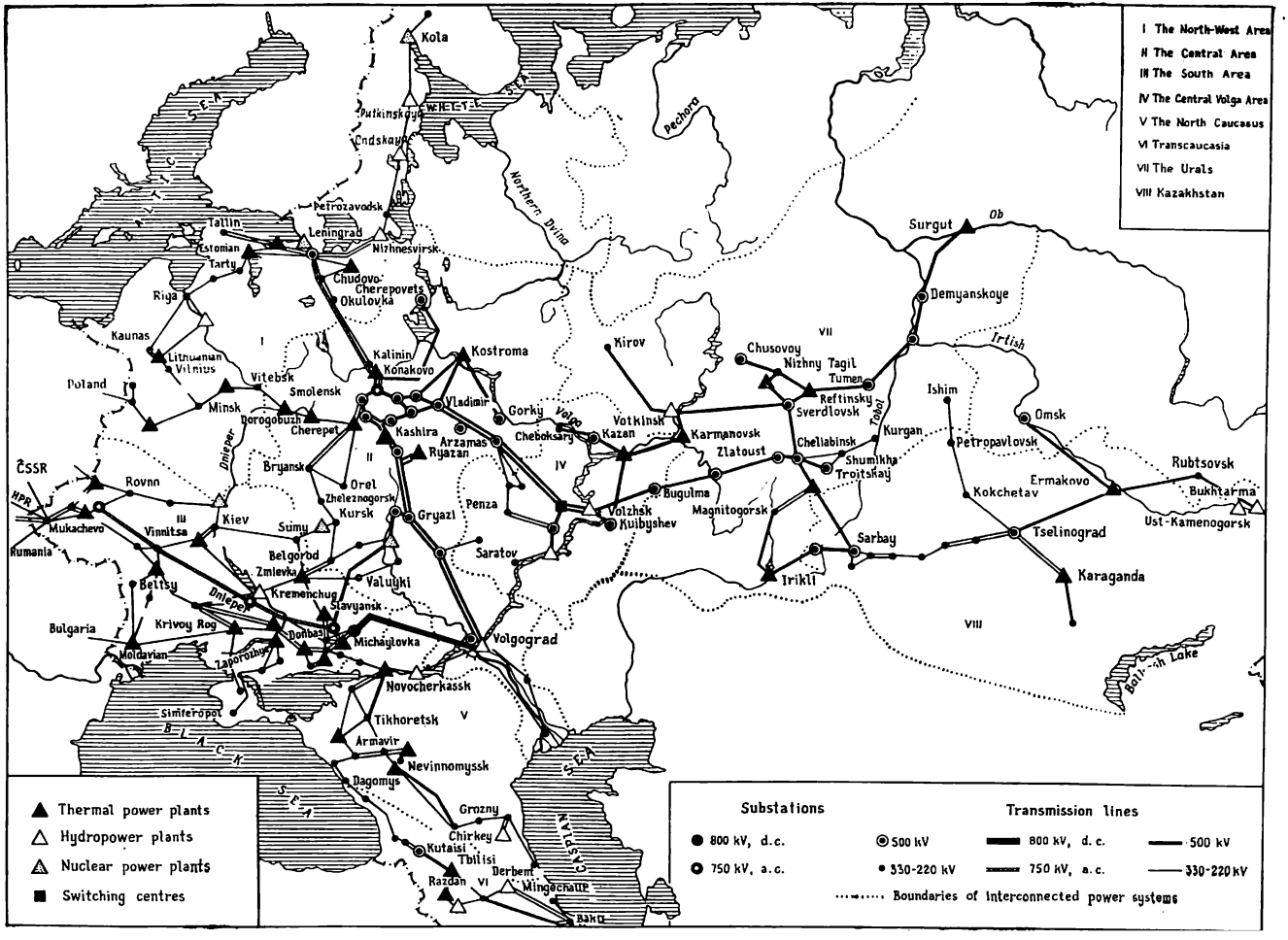

I The North-West Area
II The Central Area
III The South Area
IV The Central Volga Area
V The North Caucasus
VI Transcaucasia
VII The Urals
VIII Kazakhstan
Kola
Putkinskaya
Endskaya
Pechora
Northern Dvina
Petrozavodsk
Tallin
Estonian
Leningrad
Nizhnesvirsk
Tartu
Chudovo
Cherepovets
Okulovka
Riga
Kaunas
Lithuanian
Vilnius
Poland
Vitebsk
Smolensk
Minsk
Dorogobuzh
Cherepet
Dniepr
Katinin
Konakovo
Kostroma
Vladimir
Gorky
Volga
Kashira
Arzamas
Ryazan
Cheboksary
Votkinsk
Kazan
Kirov
Chusovoy
Nizhny Tagil
Tumen
Reftinsky
Sverdlovsk
Tobol
Surgut
Ob
Demyanskoye
Irtish
Ishim
Omsk
Kurgan
Petropavlovsk
Chellabinsk
Shumikha
Troitskaya
Zlatoust
Karmanovsk
Rubtsovsk
Ermakovo
Kokchetav
Bukhtarma
Ust-Kamenogorsk
Tselinograd
Karaganda
Sarbay
Irikli
Balkash Lake
VII
VIII
ČSSR
HPR
Rumania
Rovno
Mukachevo
Vinnitsa
Kiev
Sumy
Bryansk
Orel
Zheleznogorsk
Kursk
Gryazi
Penza
Bugulma
Volzhsk
Kuibyshev
Magnitogorsk
Saratov
Belgorod
Zmievka
Valuyki
Bessy
Kremenchug
Dnieper
Slavyansk
Krivoy Rog
Donbas
Michaylovka
Volgograd
Bulgaria
Moldavian
Zaporozhye
Novocherkassk
Simferopol
Tikhoretsk
Armavir
Nevinnomyssk
Dagomys
Grozny
Chirkey
Kutaisi
Tbilisi
Derbent
Mingechaur
Razdan
Baku
Black Sea
Caspian Sea
Thermal power plants
Hydropower plants
Nuclear power plants
Switching centres
Substations
800 kV, d.c.
750 kV, a.c.
500 kV
330-220 kV
Transmission lines
800 kV, d.c.
750 kV, a.c.
500 kV
330-220 kV
Boundaries of interconnected power systems

Fig. I.1.

This is especially true in the case of isolated power systems which have no connections with other systems, including those incorporated in movable objects, such as ships, flying vehicles, etc.

Generating mix includes various types of plants such as thermal power condensating, hydro power and nuclear power plants and heat-and-power stations.

Configuration applies to both systems and networks. By system configuration is meant a diagrammatic representation of the position of electric stations and major electric networks incorporated in a power system or individual subsystems of an interconnected power system. Network configuration refers to a diagrammatic representation of interconnections between electric stations and load centres. The power systems are interconnected with transmission lines which are used for transfer of power from one system to another. There are intersystem tie lines through which power exchange is effected.

Substations have two functions—to step up or step down the incoming voltage and to connect individual power systems.

Subtransmission networks do not directly connect the consumers while distribution networks are used to supply the domestic and industrial consumers in urban and rural areas.

At any particular instant, a power system may be at a particular state which may be defined by a set of events or processes (operating conditions). In turn, these events or processes may be described in terms of state variables such as power, voltage, current, frequency, etc.

As a physical entity, a power system may be described in terms of system variables which are dependent on its configuration and plant characteristics. Using system variables which are assumed constant within a certain range of variation of operating conditions, we can determine the relationships which depict these operating conditions in mathematical form.

A power system may be in normal operating conditions which provide for the required standard of supply at optimum values of state variables. As a further distinction, a power system may be in abnormal (emergency) conditions characterized by the occurrence of credible contingencies. Under such circumstances, state variables may deviate for a certain period of time from their scheduled values. Finally, a power system may be in a post-fault state, i.e. a condition that occurs after restoring it to normal.

1.7. Power System Automatic Control and Quality of Supply

There are the following major characteristics of the quality of supply which determine normal operation of the consumers such as electric motors, heating and lighting installations, radioelectronic

equipment: single-phase a.c. networks—frequency and voltage deviation, frequency and voltage variation, distortion of sinusoidal voltage waveform; three-phase a.c. networks—the parameters stated above plus neutral offset and departure of phase voltages from symmetry; d.c. networks—voltage deviation, voltage variation, and ripple factor.

Frequency deviation is defined as the system frequency minus the nominal frequency, the mean of the difference being taken for a 10-minute time interval. Under normal operating conditions, frequency deviation usually equals ± 0.1 Hz; in some cases, it is allowed temporarily to be equal to ± 0.2 Hz. Frequency variation is the difference between the maximum and the minimum value of system frequency with its rate of change of 0.2 Hz/s as a minimum. Under normal operating conditions, frequency variation may exceed the specified value of frequency deviation by 0.2 Hz as a maximum.

Voltage deviation defined as the system voltage minus the nominal voltage occurs at comparatively slow changes in system operating conditions. with the rate of voltage change not exceeding 1 per cent per second. By voltage variation is meant the difference between the maximum and the minimum values of the effective voltage existing on system during rapid change of the operating conditions, with the rate of voltage change not less than 1 per cent per second. The distortion of sinusoidal voltage waveform is treated as follows: the voltage wave is considered sinusoidal provided the higher harmonic voltages do not exceed 5 per cent of the voltage at the fundamental frequency.

The quality of supply depends on the time of day, weather and climatic conditions, system load changes, occurrence of contingencies, etc. A deterioration of the quality of supply may influence considerably the consumers' demand, thereby resulting in such events as a reduced efficiency of working mechanisms, poor end-products, shorter service life of electric equipment, higher rate of fault occurrence. Therefore a great deal of attention should be paid to the quality of supply in controlling system operating conditions. It is important to stress that this characteristic can be maintained most effectively in the specified tolerances by automatic regulation of voltage and frequency.

The automatic control problem of any modern power system consists in controlling the production, conversion and distribution of electrical energy and heat in both normal and emergency conditions without (or with minimal) human intervention. Being an essential part of automation*, automatic control is very important to power

* The word "automation" generally refers to an applied scientific discipline. In a more narrowed sense, we shall conform to the term to describe a set of methods and technical facilities applicable to power systems to perform certain automatic control functions.

system control since it provides for normal functioning of plant so that the whole system is operated in a most reliable and economical manner and the required standard of electricity and heat supply is thus achieved.

Automatic control in power systems is basically effected through the use of process control equipment and power system control equipment. The first includes devices responsible for automatic regulation of the main parameters of the processes taking place under both normal and emergency conditions in the units of hydro, thermal and nuclear power plant, including turbine speed, generator excitation, burning of fuel in furnaces of boilers, etc. Station-oriented control devices which may serve as the actuating organs of the power system control equipment are designed to exercise control over an electric station treated as an integrated controllable object. They include, for example, economic dispatch devices which allocate station power outputs among sets or units.

Power system control equipment affords slow control actions applied to a power system under normal operating conditions and quick control actions to resist faults that exist on a system.

The normal-state automatic control devices are actuated when system operating conditions undergo small and slow changes. Subject to automatic control in this case are system frequency, network voltage levels, etc. The fault-resisting automatic control devices handle violent system swings and intensely influence the controllable objects. They include protective relay systems operated during short circuits, standby switching-on arrangements used to restore interrupted supply to service, and automatic reclosure means to reconnect transmission lines, transformers and other equipment after their automatic tripping.

Being part of the fault-resisting automatic control equipment, emergency control schemes provide corrective actions in the case of the risk of violation of normal operation of a system or some parts thereof. The power systems of the Soviet Union utilize emergency control schemes on a large scale. Along with an extensive use of local control schemes, there is a tendency at present in the country to develop centralized automatic control systems to effect emergency control by virtue of telecontrol facilities. Emergency control schemes deal with automatic variation of generator excitation (rapid increasing and decreasing).

Of great importance are protective relay systems which are usually operated to disconnect a faulted component of a system from its unfaulted portion. In recent years, preventive control equipment has been developed to provide the system operator with information on the status of a particular system component and on the risk of its possible damage. It is beginning to be used in present-day power systems.

Emergency control schemes basically perform the following control functions: reducing the system load when frequency and in some cases voltage are decreasing (the switching-out of certain consumer loads in cases when these state variables are changing hazardously); bringing into action standby plant; automatic reclosure of those system components which were lost for some reason but could be restored to normal after a reclosure operation; and elimination of out-of-step conditions in a certain system portion whose synchronism was lost so that the resultant stability of the system is achieved. There are also some other functions for which emergency control schemes are responsible.

I.8. Dispatch Control and Its Tasks

The prime objective of all means and facilities involved in power system control is *to provide for centralized power supply of the required quality and to ensure its reliability through the use of a united operational dispatch control of the processes during which power is generated, transferred and distributed.* The management and control activities performed by dispatch bodies are very important to proper power system operation. In the Soviet Union, dispatch departments of regional control boards (RCB) are subordinate to area-level control boards (ACB) exercising control over 11 interconnected power systems which belong to the following areas: the Central Area, the North-West Area, the Central Volga Area, the South Area, the North Caucasus, Transcaucasia, the Urals, Kazakhstan, Central Asia, Siberia, and the Far East. At the nation-wide level of the command hierarchy is the Central Control Department (CCD) of the USSR United Power Grid (UPG). The CCB is under direct control of the USSR Ministry of Power Industry (Minenergo).

Area control board is involved in planning and maintaining the operating conditions of the respective interconnected power system. It also deals with generation schedules and intersystem power flows. The principal goal of the UPG that determines the tasks of operational dispatch control is the achievement of an optimum nation-wide level of electrification, with the most economical and reliable electricity supply. The fulfilment of this goal has already required much effort and is in need at present of solving many complicated problems on the basis of two approaches as follows.

The first approach calls for the introduction of cybernetic methods of management and control of the UPG, which rely on the exertion of the purposeful and optimum control actions on the grid while taking into account all key interconnections of it with other systems. Present world experience and data on trend analysis in the field show that management and control of national power grids, if void of cybernetics, would fail to meet proper technical and eco-

nomical requirements even within the next five years. The cybernetic approach, however, would be fruitful merely in the case when national power grids would be designed on the large-system principle.

The second approach deals with two interrelated problems concerning the UPG: system optimization (with the appropriate reliability factors taken into consideration) and operational control. The two problems should be answered in order to obtain conditions in which the UPG could be operated on a highly reliable basis with maximum economy.

To build an adequate theory of optimization and control of the UPG, it is necessary to study its properties in certain generalized terms so as to find and formulate the basic laws underlying its development and to design optimum control methods through the widespread use of modern mathematics (including systems analysis) and cybernetics. The key points of interest in this case are the problems concerned with the limited uncertainty of the nature of the systems under investigation and with their complex hierarchical structure, and also decomposition problems. Also important are the problems that concern the unavailability of complete information about system operation and expansion. In the face of these and other associated problems, we are in urgent need of finding an optimum combination of the formalized methods on which depend the operation of control machines and human effort involved in controlling system operation and expansion.

The expansion and growth of power systems is caused by the constant increase in the index of energy available to labor. This is typical of all industrial and domestic processes and reflects the most critical trend in the power industry in the second half of the twentieth century.

In the Soviet Union, a particular attention is paid to the growth of the amount of energy available to labor. At present, the national economy of the country is approaching the level at which it is developing mainly due to intensification of production, which means that the growth of the latter is achieved for the most part through a rise in labor productivity. It is the electrical power industry which is considered to be a very important branch of the national economy. Indeed, the use of electrical energy as part of overall country's consumption is continuously increasing. This is due partly to increasing the magnitude of that consumption and partly because electromagnetic energy is tending to replace other forms on account of its specific useful properties.

The development of power systems leads to pollution of the air. Therefore, the legal and planning framework is established in this country to ensure the removal of air pollutants from all urban areas. At the power-system level, the following measures are taken to remove harmful gases:

small boiler sets are superseded by centralized heat supply utilizing heat-and-power stations and large boiler installations having adequate chimney gas cleaners;

in urban areas high-grade types of fuel are introduced and large boiler installations are sited, if possible, outside the area boundaries;

gas cleaning installations are improved in order to obtain their efficiency not lower than 98 to 99 per cent through the use of modern electrostatic and dust filters.

Power systems influence considerably the water balance of the national water undertaking system for the following reasons.

(1) The tremendous and ever-increasing amount of heat produced by thermal power plants is removed by water, which results in its thermal pollution. Other effects concern the construction of artificial water reservoirs and flooding of the land. The raising of the temperature of the water in these reservoirs and rivers causes disturbances of the flora and fauna; in particular, this increases the growth of blue-green algae;

(2) The construction of hydro power plants causes changes in the river regime. This is especially true in siting storage reservoirs on the flooded land. As a result, certain economic and geophysical effects arise which are very complicated. Of course, they should be taken into account in assessing and establishing power system growth trends.

Nuclear power plants are advantageous in that they do not produce harmful exhaust. However, such plants should be designed on the fail-safe principle to ensure adequate radiation shielding (including failures of low probability) and disposal of the used reactor fuel.

With solutions to the above problems found, the prospects of nuclear power industry are promising. Indeed, the rate of its growth in leading countries, including the Soviet Union, is continuously increasing. At present, nuclear power plants are responsible for a higher thermal pollution than other plants. However, the use of closed-cycle water-cooled schemes will provide them with a gain over all other types of plant as to environmental protection. A very high level of safety could be achieved in countering the environmental contamination by radioactive wastes from nuclear power plants. Under these conditions, such plants could be made more safe in all other aspects of environmental protection than conventional thermal power plants.

Researchers who are dealing with the design and development of a power system as a complex cybernetic system are not armed at present with adequate methods to obtain well-devised designs. It should be stressed that finding such methods is considered a major task, because they would help to maintain constantly an optimum level of design and development work and to avoid cases when the investment in the power industry has a poor return. This task should also

be tackled for the reason that modern power systems, including ever-increasing number of regional power systems, tend to link together, thereby providing for the adequate basis for one hundred per cent electrification of the country and also for generation and distribution of power in the most economical manner.

Interconnections throughout the United States and Western Europe countries continue to grow and expand intensely. Since privately as well as publicly owned power organizations exit there, certain difficulties arise in the development of their national power grids.

In the last ten years, MIR interconnected power system belonging to the CMEA countries has been growing on a large scale. The dispatch control of this system is effected on a single hierarchical principle.

The foundations of power systems are many and varied, including economic, planning, and expansion forecasting facets which are to be treated in connection with the country's national economy. There are general, demographic and social, problems and specific problems relating to methods of calculation and optimization of system operating conditions. On the other hand, the power engineer deals with the processes that occupy on time scale the range from several fractions of a microsecond to dozens of an hour. Owing to the presence of such a variety of tasks, power systems can be studied merely with the help of advanced mathematical methods.

REVIEW QUESTIONS

1. What is a large energy system and what are the subsystems it consists of?
2. What is the purpose of an energy system and its constituents?
3. Explain the significance of the fuel-and-energy complex in the national economy. Determine the character of the links that connect it with the LES and its constituents.
4. What is meant by the energy balance?
5. What are the general and specific features of the LES?
6. Explain why the LES and its constituents are to be treated as cybernetic systems?
7. Describe major tasks concerned with power system expansion and operation control and their interrelations.
8. Give a definition, in a broad sense, of management and control activities relating to power industry.
9. How would you describe measures providing for effectiveness of energy system management and control?
10. What is meant by energy resources and power industry-associated processes?
11. What technico-economic advantages are to be gained by using energy systems, national power grids and international pools?
12. What is meant by the terms normal operating conditions, emergency conditions and post-fault conditions of an energy system; and by the terms state variables and system variables?
13. Describe the performance characteristics of an energy system.
14. Describe harmful effects of power industry on the environment. What measures would you take to eliminate these effects?

Chapter 1

Large Energy Systems. Theory of Management and Control

1.1. General

The Soviet power industry is following the way of development of the national pan-energy system which incorporates, apart from the united power grid (UPG), also united gas, oil and coal supply systems (UGSS, UOSS and UCSS). The interaction of the constituent systems results in strengthening their mutual links as work is being done to form the national pan-energy system and its essential part—the UPG of the Soviet Union—having links to connect it to the united power grids of other countries. The process of transfer to a higher form of organization of the power industry is characterized by an ever-growing generating capacity of plants, which becomes commensurable with the energy produced by geophysical and even outer space phenomena, and influences increasingly the environment. Modern and especially future needs associated with this process call for new theoretical and practical approaches to be devised to help power system management and control problems.

To deal with the present-day situation and, of course, to provide for due direction of development in the future, the systems analysts who are investigating problems concerned with automatic control and dispatching in the power industry must treat the latter as a large expanding system of cybernetic type and as part of a larger national pan-energy system also incorporating the branchwise subsystems (UGSS, UOSS and UCSS). These subsystems have a complex and hierarchical structure with a large amount of feedback and constitute, therefore, large systems. Thus we shall treat the power industry, in accordance with modern scientific concepts, as a set of large systems.

In the next 10 or 15 years, a drastic increase in the size and complexity of large systems of the power industry is likely to occur. At present the national pan-energy system (NPES) encompasses everything between energy resources and utilizing plants.

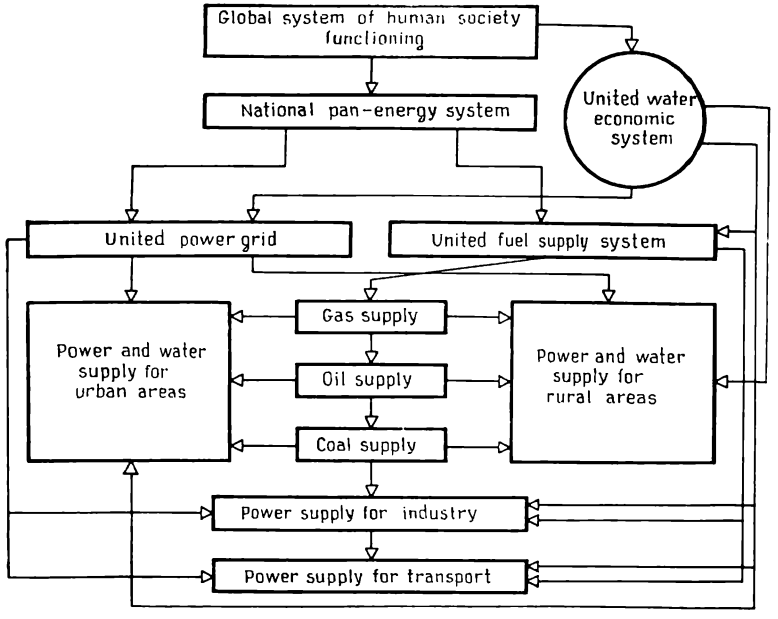

Global system of human society functioning
National pan-energy system
United water economic system
United power grid
United fuel supply system
Power and water supply for urban areas
Gas supply
Oil supply
Coal supply
Power and water supply for rural areas
Power supply for industry
Power supply for transport

Fig. 1.1

The national pan-energy system (NPES) is a complex hierarchical man-made system that incorporates a set of special-purpose systems (Fig. 1.1). They include power systems, centralized heat, gas, oil and coal supply systems, and the nuclear power system, which is being developed.

There are various links (Fig. 1.2) that connect the pan-energy system with the national economy as a whole, with other branchwise complexes, and with the environment which is of relatively great consequence to man nowadays. In the figure, the thick lines (▬) designate connections for power supply, the thin lines (———), management and control data flows, and the dashed lines (— — — —) show information flows.

Unlike other man-made systems, the national pan-energy system has the following characteristic features:

(1) the end product is substantially versatile and important to the national economy;

(2) the responsibility for economical and continuous electricity and heat supply;

(3) feasibility of major connections (electric networks, pipelines);

(4) the continuity of processes associated with power generation and consumption. From here stem the advantages resulting from

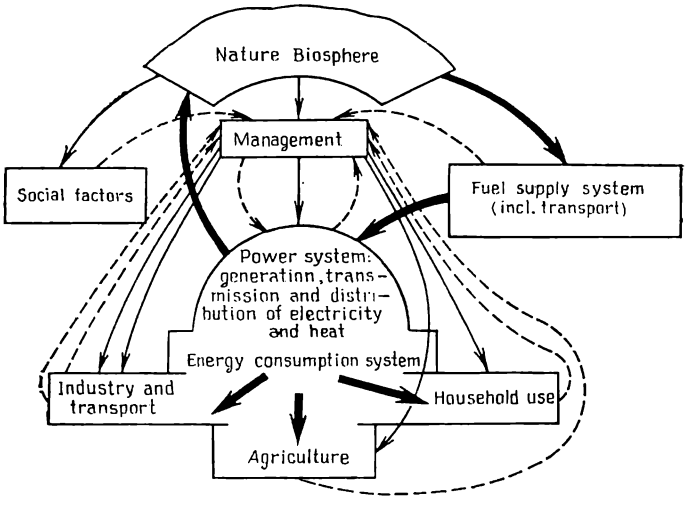


Fig. 1.2

combined operation of geographically distant systems because of their staggering;

(5) the global nature of large energy systems implies that their structure would be complex during transformations into the united power grids in both the Soviet Union and abroad.

The growing of the power industry into the form of pan-energy system has led to the advent of power science. Included within the framework of power science are the theory of optimization and the control of large energy systems which are developing on a comparatively self-contained basis.

The united power grid, a unique large energy system, is the basis for planned electrification of the national economy. The principal goal of the UPG is to achieve an optimum nation-wide level of electrification and to ensure the most economical and reliable electricity supply.

The fulfilment of this goal has already required much effort in terms of solving many complex problems. If we touch upon the optimization of development and operational control of the UPG only, the number of such problems will be sufficiently great.

There are two conceptions formulated for the problems involved. *The first conception* calls for transfer from automated techniques for the operation of the UPG to cybernetic control methods. This should provide for the purposeful and optimum control with all critical links taken into account. Present world experience shows that management and control of national power grids, if void of cybernetics,

fail to meet proper technical and economical requirements even within the next ten years. Therefore, it is important to stress that the further development of cybernetic techniques for power grid control should not be tailored to the parameters depicting either the existing or projected grids. On the contrary, the most beneficial way in this case would be to design a given united power grid, as a large automated system, from the very start.

The second conception states that optimal systems planning and operational control are two interrelated problems. To obtain that situation, the UPG (as in the case of the pan-energy system as a whole) should be oriented for a relatively independent theory of optimization and control.

In a nutshell, the goals sought by developing the theory of optimization and control for pan-energy systems may be defined as follows: using the generalized information about the investigation into the nature and the properties of pan-energy systems, we shall try to establish basic trends in their development and reveal laws underlying the principles of control of such systems through the wide use of modern techniques of systems analysis, including mathematical and cybernetic means and methods.

This approach must take into account the following main considerations:

(1) a constrained probabilistic nature of the investigated systems;

(2) their complex hierarchical structure;

(3) the need for scientifically based decomposition of systems;

(4) complete or partial uncertainty of information handled by power engineers.

Management and control of power industry expansion and operation. Although management and control problems were often treated as separate entities, they are acquiring now many features in common, tending to become a single specific problem of management. Here and elsewhere it implies the finding of solutions to the choice of the most beneficial complex of deliberate actions being exerted upon a large man-made system, which help to achieve the sought goals. This approach accords with the general trends of scientific and technological progress aimed at rapid realization of proposed advances on science and technology. To embody these advances would require the appropriate changes in expansion planning policy and also the development of new methods of operation of large power systems in advance of their construction.

The increasing importance of links between the UPG and other systems. The links will influence the system's parameters to such an extent that in terms of management and control it should be considered as a subsystem of a certain global system in which many subsystems with mutual power- and information-conveying links

(Fig. 1.2) interact with one another. This would lead to a situation in which the need arises for the rearrangement of concepts depicting information available to the subsystems and of the practical methods to process it.

When investigating power industry management and control problems, information is to be treated in more pragmatic terms than those afforded by Shannon's statistical theory, since it is such versatility with which one could achieve directly the given objectives that is important to control activities. To work out the concept worth of information, it is feasible to determine an increment in the probability of achieving the objectives before and after the reception of information. The determination of the useful rate of data transmission over communication channels should be based on those characteristics which primarily reflect the purpose and the role the data play in management and control of the UPG. This concerns both representation and control information.

Though information that describes events occurring in the realm of power engineering is chiefly analogous, it must be utilized in a digital (discrete) form. In this connection, sampling intervals and quantizing steps should be determined on an adequate basis. There are very important problems concerning data compression as well as screening of data during its transmission through the different levels of a hierarchical control system. Note that at present these problems have no secure theoretical footing and would be treated so as to meet in the first place grid operational control requirements.

However, the questions under consideration, as looked at from a somewhat differing point of view, are also critical in connection with management and control of the UPG expansion. It should be stressed that even if we obtain the absolutely complete description in terms of information, of a united power grid as part of a certain large system, we cannot utilize it in practice because of great diversification and dimensions of tasks to be tackled. A way out is to develop new methods of building information models, including decomposition of complex systems and equivalent transformation of individual information subsystems; connected with this approach are the problems of information similarity.

Another important point is that the existing optimization criteria utilized in power science would seem to vary under the action of ever-growing links between subsystems. The criteria that are determined at present as local ones, related purely to power engineering, usually deal with the minimization of the objective function based on incremental fuel rates and discounted costs. It appears that they would be subject to a greater number of constraints in the future or probably be replaced with new criteria. As a result, new mathematical methods would be introduced.

As stated above, the UPG is a large expanding system. To determine key lines to be followed in developing a control system for the UPG, it is essential to remember that control systems for power systems and the bodily power industry are likely to constantly expand. These dynamic properties should be considered as major ones when building the theory of management control systems (MCSs) and automated dispatch control systems (ADCSs) concerned with the power industry. Also, changes in methodology should be taken into account, a feature that reflects itself in a variation of mathematical models in response to the changes taking place in the power engineering technology, in the fuel balance and in the relationship between the UPG and other subsystems which constitute a global system "nature-human society-national economy" (Fig. 1.2).

In view of the advances being gained constantly in the field of computer engineering, we may say that the problems relating to the expansion of control systems for the UPG and the power industry as a whole are never ending. Sticking to that view some researchers may consider the problem of power industry control as an immobile and local one which relates merely to electrical power engineering and would wrongly orient themselves as to the trends of development, implying that the complete solution to that problem is possible.

1.2. Management and Control of Pan-energy System Expansion and Operation

The fact that the problems of controlling the pan-energy system expansion and operation should be dealt with on the basis of a single approach does not preclude the power engineers from using practical methods of control which feature certain, and sometimes sensibly large, differences. In the near future, an urgent problem will be providing the UPG management control system with an automated data acquisition and processing system. As stated above, relevant data should be defined by considering the power industry as a large system. It is essential to determine suitable forms of data representation. Another important point with the problem is that the quantitative terms in which information is expressed must allow it to be dealt with by unlike criteria. Thus such criteria that would not be described in cost terms could be compared directly on a common basis. The development of management and control activities in the power industry must follow the lines which enable the upper levels of the command hierarchy to gradually strengthen and expand, and the lower levels, to acquire greater sensitivity (Fig. 1.3). It appears that the need to take into account the effect of the interrelated subsystems (Fig. 1.2) on the power industry and the pan-energy system as a whole would reveal itself more and more just at the

upper levels of the command hierarchy responsible for the control policy.

The UPG operation control. It would seem that the UPG operation control should become more information-oriented, with factors of global character being taken into consideration. In such circumstances, the upper levels of the command hierarchy (Fig. 1.3) would be given new properties which would allow them to be treated as a super-system providing for automated dispatch control. As a result, there would emerge the problems associated with the assessment of the effectiveness of intersystem links and of the methods for data exchange between the subsystems (Fig. 1.2). Important to the study in the field would be the cases where a centralized control hierarchical system (Fig. 1.3) should be subject to partial decentralization.

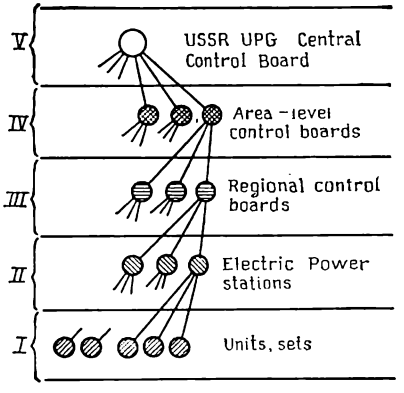


Fig. 1.3

As to control of the operating conditions of the existing national power grids, it is important to stress that in the light of present-day ideas those steady-state conditions on a system are considered to be its optimum operating conditions under which the consumers are provided with electrical energy of the required standard at minimal operating costs referred to a given time interval. However, a more distinct definition of optimization problem which covers the influence of the UPG not only on the power industry but also on the human society as a whole, would require a huge amount of refinements and additional investigation into a great number of critical factors, with account taken of constraints being treated as extra criteria necessary for maintaining scheduled operating conditions. In particular, subject to objective estimates on a comparative basis should be modern mathematical optimization methods (gradient and others) which are used by different researchers and are thus given different names on unaccountable grounds.

Optimization of the UPG expansion control. This primarily concerns the determination of grid structure seen in the light of its dynamics and the choice of adequate policy of its development as well as control equipment to keep at a minimum the total discounted costs and to take into account, to some extent or another, the criteria concerned with the optimization of grid operating conditions while handling the additional factors stated above. Concurrently with the use of the synthesis method applied to the

subsystems, the appropriate regulation and control facilities should be chosen.

Thus, we may say that the optimization methods to treat the control of expansion and operation (operating conditions) of the UPG should be devised on the basis of numerous criteria and extremum conditions. This would lead to the advent of new approaches to the problem as compared to present-day investigations which are apparently tending towards a single major criterion. Though existing approaches are working with certain constraints and additional criteria, this is done in a rather restricted way and the basic approach relies on a single extremum principle.

Optimization criteria. In the near future, probably not so distant, the development of the theory of control of the UPG will focus attention on those conditions and optimization criteria which reflect harmful effects of the power industry (including air and water pollution) on the biosphere, agriculture, fishery, etc. The indicators characteristic of demographic factors will be defined in a more explicit form when dealing with engineering designs.

It appears that forecasting methods should contribute actively to the solution of the practical problems related to power industry expansion so as to take into account to a greater extent advances in science and technology and growth rates in labor productivity. Even under the existing conditions certain "additional" criteria become more important than "major" criteria. For instance, there is a need to produce "pure" energy having no harmful environmental effects, namely, a specific problem of removal of air pollutants from large urban areas, whose action might be disastrous under certain weather conditions. This has forced already system-planning engineers in the United States to change in some cases the siting of electric power stations during system expansion planning or to freeze the load on those existing electric power stations which could be otherwise operated in the most efficient manner in accordance with present-day optimization criteria.

Dealing with optimum control as applied to the above problems of system expansion and operation, one must utilize formalization methods that require finding the extremum conditions for a complex objective function J, which depends on a number of estimates (y_k) of the properties of a large system

$$J = f(y_1, y_2, \ldots, y_k, \ldots, y_n)$$

It seems that practical optimization criteria based on the function are very difficult to find under the existing conditions. These difficulties, however, should be overcome in order to determine a criterion of a comparatively general character (or an adjusted set of criteria) which would fit the optimality conditions for both existing and projected systems. Thus practical engineering methods would

reflect to the fullest extent the general and unique optimality criterion which would be formulated in terms characteristic of the socialist society as "the most effective and reasonable utilization of material resources and labor force to satisfy the growing needs of the society members". The important point is that certain criteria are difficult to adjust with one another or to express explicitly in uniform terms. This requires the entirely new approach to optimization problem, which would replace a "precise" determination of one extremum point corresponding, for instance, to unique optimum operating conditions (or unique optimum plan of system expansion) with the establishment of the strategy to maintain system operating conditions or support system expansion.

It would appear that the efforts to overcome or to reduce the difficulties associated with direct formalization of J should be combined with sensitivity-related methods allowing for a comparatively simple way to reveal the system response to a variation of certain factors involved. In this connection, it is important to stress that the function subject to minimization within the region of its extremum (or extrema) is characterized, as a rule, by a hypersurface with a fairly mild slope. However, the source data relating to the problems under consideration are considerably incomplete and probabilistic. This means that we cannot treat management control systems belonging to the power industry as the systems that fit rigorous formalization criteria.

With all the characteristic features of the UPG and its associated subsystems taken into consideration, the use of a system of algorithms whose realization would involve human effort may be envisaged as a feasible, and moreover as an essential approach. Thus the ergaticity principle as applied to algorithmization problem makes it possible to tackle it heuristically and, when there is a need, to subject a complex objective functional to a forced change by using the experience and intuition of human operators involved in control activities. It would, thus, be bad practice during expansion planning of management control systems for the power industry to imply that a fully automated closed-loop control system of cybernetic type would be implemented at once, with the four intermediate development stages omitted (see Fig. 1.4).

1.3. Power Industry Cybernetics

Being part of the global system to support life adequately, the power industry interacts with the environment (biosphere) and is related to certain social factors. A power system, in its turn, comprises a number of subsystems, which constitute large systems whose interaction is effected through the use of direct links and large amount of feedback. The control of such power systems and their interre-

lated subsystems as related to expansion and operation problems may be described as a variety of purposeful control actions which could be optimized to some extent or another. Thus, power systems may be treated as cybernetic systems. This means that investigation into them usually employs or should employ, anyhow, cybernetic methods.

The advent of cybernetics has led to introduction of a great variety of scientific and technical disciplines. As applied to the power industry, cybernetic methods are closely related to the use of all types of modelling and the theory of complex automata, which provides for the automatic operation of various systems with the help of electronic digital computers which belong to the steadily growing field of technology.

Cybernetics depends for its development on the study in the processes that deal with control and processing of information flows. The theory of information as applied to power industry problems should follow new lines of development primarily concerned with the ability of power engineers to analyze information-related processes on the basis of the existing hierarchy of objectives. It is the approach with which the application of cybernetic methods to the power industry as well as the development of its management control systems and automated dispatch control systems would yield great benefits. In this connection, an urgent problem is to create new methods of conversion and presentation of information, which would be applied specifically to the power industry and would differ from the known Shannon-Kotelnikov methods in that a relationship would be established between them and the goals to be attained in control activities.

The attention of the researchers who deal with these information-related problems encountered in the field of power industry as well as with other problems relating to power-system cybernetics should be focused on the important group of mathematical ideas and hypotheses cybernetics borrows from mathematics, theory of information, logic, electronics, automation and other scientific disciplines.

The important point with the power industry and its related problems is that they are extremely influential in cognitive and social terms since large power systems are substantially associated with such factors as political, demographic and others. The methods of analysis of the various processes occurring in nature, human society and biosphere are putting in the forefront as to their influence on practical needs and scientific methodology. The role played by the power industry in human activities is constantly increasing as the power produced by it becomes commensurate with the power resulted from certain phenomena that tend to change the face of Earth.

All forms of energy affect the biosphere in the course of their production, transportation and consumption. This creates the problem of purity of energy, which is critical since life is sensitive to harmful environmental effects. Thus we may conclude that it is cybernetics of large power systems that should be considered as a most important facet of the hierarchy of the sciences involved, especially with the social importance of the power industry taken into account. Power system related methods are increasingly utilized to study any types of large systems and determine their operating conditions and effectiveness. Thus it is obvious that the cognitive capabilities of power science and associated cybernetic methods are of great significance.

It is no mere chance that many Western publications concerning scientific-technical, economic, or philosophical topics tend to utilize certain power engineering concepts, for example, energy flows. Though we do not intend to discuss the problem in this book, we must stress, however, that familiarization of research workers with theoretical foundations of power science will lead them eventually to certain power engineering concepts of philosophical character. It is these concepts that allow for the transfer to the general theory of cognition on the basis of analysis of power engineering problems.

The difficulties encountered by researchers during investigation of present-day complex power systems call for the employment of many other specific methods of modelling along with those mentioned above. Among them are methods and techniques of cybernetic modelling, which basically reduce to direct modelling of certain functions of the system under investigation by virtue of the functions of a model; in this case, no attempt is made to discover the nature or structure of the events occurring in both the system itself and its model. This method is an extension of one of the fundamental principles of cybernetics which tells us that an examination of a system is based on the investigation of its behaviour. This means that a researcher observes the state of the system outputs produced by the activated system inputs, the actions applied to the latter being available from either the researcher himself or a higher level of control. In such circumstances, a system is treated as a converter that transforms input states into output states and complete definiteness of the system is implied provided that the appropriate type of system variable conversion is defined. This conversion may be expressed in an abstract form irrespective of the real physical character of the input and output variables existing in the system. The physical character and the inner structure of a model may have nothing in common with the study object. These features are principally typical of cybernetic modelling in contrast with physical and mathematical modellings which try to reflect the processes occurring within the investigated system, i.e. the system of the study object. In physical modelling, the similarity criteria must be satisfied and the

same structure of the study object and the model must be chosen; also, the boundary conditions must be similar. Mathematical modelling requires that the equations which describe the processes existing in both the study object and the model be isomorphous.

In the case of cybernetic modelling, similarity conditions should be applied merely to the process in which system inputs are converted to system outputs; this means that similar in this case should be system functions only. This arms a researcher with extra operational capabilities not encountered in physical and mathematical modellings.

It follows from the foregoing that cybernetic modelling makes it possible to find out the functional relationship between the study object and its environment and chiefly deals with open systems, which are influenced by the environment and respond to this influence. It is for this reason that the methods of cybernetic modelling are important to the investigation and optimization of certain complex problems such as the interactions of power systems and biosphere systems. The structural modelling aimed at the discovery of the processes occurring within particular subsystems is not applicable in principle to the solution of these problems, which can be solved, however, by the methods of functional modelling devised to reflect interaction of inputs and outputs of a black box. Using the concept of a black box, a researcher is able to depict functionally complex processes, both natural and artificial, that take place in the interrelated systems, but he does not concern himself with the structure of these processes in the course of his analysis.

There is an ambiguity in choosing terms to describe the new methods and techniques of modelling. For example, the terms *model* and *modelling* are often used as the equivalents of the word *theory* or even *hypothesis*. Some authors replace the word *similarity* with the word *reduction*, etc. We suppose that such discrepancies may be justified to some extent.

Though the new lines followed by cybernetics in the course of its development are not unique ones, they are typical at present of the extensive scientific discipline called the power system cybernetics.

Of course, the practical techniques and methods provided by cybernetics should not be overestimated. Like in any other branch of science, the applicability of the various hypotheses and methods of cybernetics is determined from experimental data.

The optimization and planning of the operating conditions of power systems are connected with the employment of computers. There have been a number of computer applications in the art. The computers available at present are used for the optimum planning of the operating conditions of thermal power plants and of transmission lines, for system voltage control, etc.

Finding solutions to the optimization problems relating to management and control of power system operation and expansion considerably depends on the study into the accuracy of the methods of mathematical modelling. To choose the useful mathematical model (description) and the respective iteration method, it is necessary to determine the overall error, including the errors introduced by the model and method as well as the errors that result from the inaccuracy of source data and the round-off of the obtained results.

On the basis of the investigations performed we may conclude that methods must be developed which would take into account the uncertainty of source data in solving optimization problems concerned with designing electric networks.

The present-day methods of calculation of steady-state operating conditions basically deal with the general network theory problems, diakoptics, the determination of conditions under which unique solutions are found for load-flow and convergence problems and with various modifications of the Newton method, including the Newton-Raphson method and others. For calculation of the steady-state operating conditions, use is made on a large scale of the Newton method and, on more rare occasions, of the Seidel method; this is explained by the fact that the employed computers have a high memory capacity and a large speed of operation. In modern power systems the statistical nature of system parameters and associated disturbances should be taken into account in calculating system operating conditions.

The effect of the events of statistical nature on system operating conditions is growing as the power system becomes more complex; plant and equipment are expanded; links between system components grow; automatic regulation and control schemes are expanded, and so on. In such circumstances, special attention should be focused on system reliability factors which tend to acquire some specific features.

To assess power system reliability, we must determine how failures associated with particular system components affect the operation of the power system as a whole. Thus the calculation of system reliability factors requires that data on particular component reliability factors be available. The important point with a complex power system is that its overall reliability should be assessed and that statistical occurrences should be taken into account when dealing with system transient conditions.

Computer applications in the power industry encounter a key problem involving the design and construction of hierarchical systems to control interconnections of power systems. Such hierarchical control systems must be provided with adequate software and conversational programs, which allow human control operators to communicate with computers.

Some experience has been gained by now, concerning the design of these hierarchical control systems and the use of computers and analog-digital devices as part of the control loop. It is important to stress that computers can tackle control tasks effectively when they are equipped with adequate program sets that include operating programs to handle engineering problems, service programs to provide for man-machine communication, and operating systems to ensure efficient computer operation. Such program sets are called software. The software of an automated dispatch control system (ADCS) is designed as a single system of programming aids, which helps to handle power system dispatch control problems and to control the operation of computers which are part of the system itself; thus it constitutes a specialized operating system.

The problems involved in operating a modern, complex power system with the help of computers are many and varied. For example, digital excitation control devices are being designed. Further development of such devices will lead to the construction of a combined digital controller to perform excitation control, speed governing and to handle actuation elements of some emergency control schemes. Note that the above digital excitation control devices can also provide a basis for the development of a commercial excitation control device with a high algorithmization capability. The working principle of this device would be compatible to a great extent with the principles of adaptation, self-test and self-recovery. It should also be noted that the successful use of digital data processing methods as applied to control of transients occurring in power systems is the result of the advances encountered in the field of microelectronics, and many difficult problems may be solved in this way.

There are many computer applications for power system state estimation and identification. The comparison of the numerous mathematical methods used in the field receives a great deal of attention. It is important to stress that the complexity of power installations is steadily growing, new forms of energy as well as new methods of power generation, transmission and consumption are being introduced. The system-planning engineers should generally deal with a complex, large system which is growing into a cybernetic system. However, the present-day power system expansion planning does not utilize to the fullest extent adequate scientific methodology. For example, the value of feedbacks established between the subsystems of large systems is taken into consideration insufficiently.

The recent investigations show that the probabilistic character of source data should be given due attention in treating a power system as a cybernetic system. It seems that the conditional probability approach may be and should be useful in handling the source data on which the determination of load values depends.

An analyst who does not employ cybernetic methods usually fails to utilize modern computers properly. Although it is certainly true that man requires these very powerful tools—computers—it should not be forgotten that they could not replace his ability to think and that his contribution to machine effort during automatic and cybernetic type of control should be considerable. These things are especially important in our time that sees how planning work approaches its highest tier where the power industry is to be treated as an entity comprising complex and growing systems, i.e. cybernetic systems.

It is evident that investigation into a power system treated as a cybernetic system should take into consideration all its links established between other systems and subsystems of the national economy.

There are certain specific aspects connected with power system planning optimization. This primarily concerns the fact that the employed functional relationships and equations are nonlinear and the degree of this nonlinearity is substantially high.

The above discussion leads to the following conclusion: power system planning is a cybernetic problem since a power system connects other systems, particularly through the agency of time-dependent feedbacks so that current events are influenced by early events.

The analysis work on an operating power system also requires critical changes in the fundamental approaches. At present, the power system in steady state or during transients is generally analyzed on the basis of certain static conditions and parameters which are applied in some arbitrary manner to the dynamic behaviour of the system. For example, solving the problem of optimum allocation of the load among the stations of the system does not take into account the fact that most of the characteristics of station equipment, as well as of consumer installations tend to vary continuously.

The important point with the analysis of modern power system operation is that those parameters and interrelated internal links should be taken into consideration which undergo the most critical changes during operation. These considerations should, therefore, provide a basis for the development of a new approach to the analytical investigation into a modern, complex power system. The new approach would yield, of course, substantially differing decisions as compared with the results of early analysis work which sufficed a relatively simple power system.

Automatic and cybernetic control of a power system should also be dealt with by virtue of new analytical tools. It would appear that automatic control of a power system in transient conditions should be supported by solving in a rather rapid way the simultaneous differential equations that describe how the transient processes under investigation run. A useful solution to the problem would be

as follows: with the system maintained in the initial operating conditions, measure its initial state variables by means of the suitable devices; input the data so obtained to an automatic computer to solve the simultaneous differential equations that describe the behaviour of the system.

Finally, the analysis of a modern, complex power system treated as an automatically controllable system should be put on a new scientific basis. The existing methods should be abandoned which are devised to deal with the behaviour of the investigated system by using the preset values of its parameters. Instead of this, good practice would be to calculate and estimate those changes in the parameters for which cybernetic control devices are responsible.

An urgent problem is to construct new regulating and control devices based on adequate design methods. The design engineer should not focus his attention (as he usually does) on the description of system behaviour, but he must try to reveal the methods which would help him to direct that behaviour along the desired line and to express the resulting changes quantitatively. In such circumstances, the cardinal point of interest is not the accuracy of the design method evaluated in terms of the source data, but the accuracy with which the necessary corrective actions are being worked out in response to the information about the progress of the process under investigation. Thus it is a feedback-type cybernetic control in which account is taken of the interactions between the control devices and controllable object and the environment.

We see, therefore, that cybernetic approach is essential in solving problems associated with the design and operation of a modern, complex power system. If the analysis work on a power system being investigated yields valid pertinent data, this practically means that the system is giving economy in capital and maintenance costs; if not, ineffective expenditure will follow. Though it may seem paradoxical we may say that proper realization of the methods of cybernetic programming and control for power systems is equivalent to obtaining considerable extra revenue or greater increase in power production. Thus we can emphasize that the problems relating to power system cybernetics are of great importance nowadays and the near future will require new decisive solutions to them.

1.4. Conditions of the Consumption of Electrical Energy

Prediction of future events is essential for management and control. Tackling the problem in connection with a power system means that changes in system generation of consumers' load or demands must be predicted for comparatively short or long terms ahead. To deal with consumption of electrical energy on a secure theoretical

footing, we must solve a number of diverse problems having both practical and methodological significance which often go beyond the realm of power engineering.

The consumption of electrical energy is related in a way to the use of all other resources available to a given country. On the other hand, the country's total energy requirements are connected in a certain rather unique fashion with the economic, scientific-technological and cultural level of the country's population. Moreover, energy consumption may be considered as a measure that reflects the economic and cultural development of mankind as a whole. For instance, in the Stone Age, a human being required 0.3 to 0.5 kW h per day. Nowadays, however, this figure is in the range of 200 to 300 kW h per day.

We may see that there is a similarity between the curves that depict the way in which man consumes energy and collects information generally representing his cultural advances. This may be explained by the fact that the development of the material-and-technical basis of human society depends on energy production. The amount of information collected by man up to the present time equals 10^{14} bytes, which corresponds approximately to a consumption of 6×10^9 tons of equivalent fuel*. Note that uneven distribution of energy production among countries and continents is related to differences in levels of their economic and cultural development.

The level of electrical energy consumption is, therefore, a complex function of the following: the time of day and/or year, the weather conditions in a given area, and the social and economic structure of a given country or area. The conditions of power consumption affect the real tariffs at which energy is sold. Some authors show how the real tariffs change with an increased level of electrical power consumption. In the United States, the data accumulated within the period of 1920-1960 indicate that there was a 16-fold increase in electrical energy supply, accompanied by a 3-fold decrease in the real average tariffs. A similar tendency was noticed in other countries. It should be emphasized, however, that with differing users tariffs decrease differently. In the case of small domestic users the rate of tariff decrease is considerably greater than that for large industrial users. The figures above that describe the situation in the United States may be interpreted as follows: the cost of electrical energy supply for domestic and industrial users decreased respectively by about 80 and 60 per cent. In Great Britain, a ten-year period between 1950 and 1960 saw tariff decreases for domestic and industrial users of 50 and 5 per cent, respectively.

---

* 1 ton of equivalent fuel produces a heat energy of 7×10^6 kcal. 1 kcal = = 4.1868 kJ.

There are a number of reasons for tariff decreases. It should be noted that the cost of power transmission and distribution is important. In most countries, a variation in the cost of power production brings about no decrease in tariffs. In countries with thermal power plants, it was a rise in prices that hindered the cost of electrical power from lowering; the cost reduction was due to an increase in the thermal plant's efficiency and units enlargement. Should the countries with a great number of hydro power plants have their cheap hydro resources exhausted, the cost reduction of electrical energy would stop. If the cost of production of electrical energy remains unaltered, or even grows, and the cost of its transmission and distribution lowers, then the tariffs for large users reduce at lower rates, though for the case of small users the tariffs (which mainly depend on the cost of electrical power distribution) decrease significantly.

In the near future, nuclear power plants will play an essential part in the production of electrical energy and determination of tariff policy. There are reasons to suggest that in the future the cost of transmission and distribution of electrical energy will acquire greater significance for most consumers, with the result that the described relationship between electrical energy supply and tariffs will become more distinct.

The electrical energy consumption problems are directly connected with a constantly growing level of electrification of the national economy. This level may be reflected in the so-called coefficient of electrification of the energy balance, which defines that portion of the total consumption of all forms of energy for which electrical energy is responsible. This coefficient is one of the essential indicators used to describe the level of electrification of the national economy and the structure of the energy balance. The electrification level is steadily growing because of the following factors: the replacement of manual labor in the production areas and services by machines using electric drives; the replacement of installations that work directly on fuel, steam, or hot water with electric installations; and the replacement of fabrication processes which utilize directly various forms of energy with processes based on the use of electrical energy. It should be emphasized that not only technical, but also economic considerations must be taken into account when we decide on the use of electrical energy. The economic considerations must tell us whether or not the production of electrical energy is economical, including such factors as the methods involved, the extent and level of the power industry development, and the technico-economic characteristics of the available natural energy resources.

Thus, we may say that there exist direct links between the ways, in which electrical energy is consumed, and the development of the whole national economy and its individual branches. Within a given period of time for a given country or large economic region there are

specific optimum relationships and proportions which determine the use of electrical energy and other forms of energy and are characterized by an optimum coefficient of electrification and optimum structure of the fuel-and-energy balance.

As the technological progress utilizes electricity on a large scale, the mix of electrical energy consumers tends to change in the direction of a greater use of high-temperature and electrochemical processes. Owing to the essential part played by electrification in the social production, close links are created between the use of electrical energy and the development of the national economy. In the Soviet Union, the coefficient of electrification in the energy balance increased by a factor of 15 from 1930 to 1970; presently it amounts to about 30 per cent. The value and rate of that change in the coefficient are the measures that reflect the combined effect of many factors on which the level of electrification of the national economy depends.

The growth of electrical energy consumption is related to the growth of gross output. There are data available from the United Nations showing that during the period from 1960 to 1965 the world gross output rose by 31 per cent, the industrial output, by 40 per cent, and the electrical energy consumption, by 46 per cent.

An essential combined indicator that describes the part played by electrification in the national economy is the relationship between the rates of growth in the power consumption and the national economy.

The need to utilize electricity in the social production and for household uses is becoming increasingly important. This requires a much greater rate of electrical energy consumption for the production of social products than for key branches of the national economy.

When determining the effectiveness of electrical energy consumption, it should be borne in mind that construction costs of the equipment for electric stations and networks are repaid rapidly on account of savings in the cost of industrial production due to the growth of labor productivity. Each kW h used in agriculture gives a saving in labor costs of 1.5 to 2 man-hours. Capital investment in electrification of railways would give returns in 6 to 8 years. Thus the transfer of railways onto electric power yields substantial savings which may amount, according to some authors, to the total annual expenditures for railway electrification.

The use of electricity at home and in the services can be estimated primarily in terms of social factors. These concern, in particular, cuts in the cost and the improvement in labor conditions as related to the provision of self-service facilities for people. The completion, in the near future, of electrification of household work would yield savings in labor costs amounting to not less than 8 000 million man-hours, which would give people an increase in spare time.

Thus, we may see that the increase in the use of electricity provides for the economic and cultural development of the country.

1.5. Control Systems

Man-machine problem and trends in it are essential for developing management control and automated dispatch control systems for the power industry. The important point with the problem is that man should be engaged in control activities at all levels of control. However, human effort involved in control tends to vary, and machine is given control over an increasing number of functions which involve less creative activities.

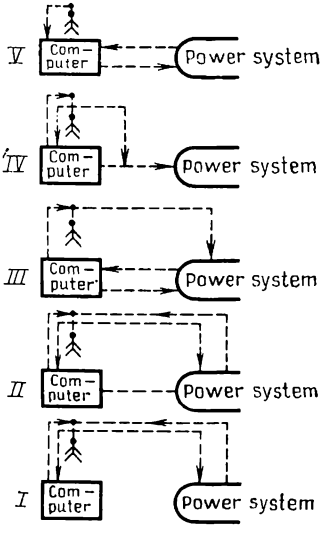


Fig. 1.4

A power-system control system is designed to effect two types of control actions which apply respectively to the united power system treated as a controllable object and to the control system itself. Power-system forecasting and planning methods, especially concerned with control of operating conditions, must provide for adequate determination of the diversity of the control system, which should be not less than the diversity of the controllable object. This ensures a condition in which a control system has sufficient flexibility and can adapt itself, on both qualitative and quantitative basis, to growth and expansion of the power system and to any variations of its connections with the environment, i.e. with the associated subsystems (Fig. 1.2).

We may suppose that within the period between 1980 and 2000 the desired variety of control actions applied to power systems can be attained by using merely the principle of ergaticity which implies that human and machine efforts should be combined on a purposeful basis. The investigation into the algorithmization of control processes as well as the development of modern mathematical methods for all stages involved in the expansion of control systems (I-V in Fig. 1.4) should be based on the ergaticity principle. It is for this reason that human effort is to be involved in all these stages and man should play his part in the activities within the scope of a most developed stage (V). It would appear that this stage should be gradually transformed to provide for the possibility of creating self-learning systems belonging to the "machine world" systems.

A schematic diagram of such a machine world system (Fig. 1.5) comprises unit *1* to handle data on a set of events occurring in a power system and in its connections with the environment. It is assumed that such events occur during system expansion or control. Unit *1* operates to choose and form major concepts associated with causal-consequential and spatial-temporal links. In units *2* and *3* hypotheses are built on the basis of the theory of games and statistical decisions, which are realized by virtue of heuristic considerations. Model and environmental designs are formed in units *4*, *5* and are then tested and compared in units *6*, *7*, *8*. As a result, decisions are made which correspond to events that might occur.

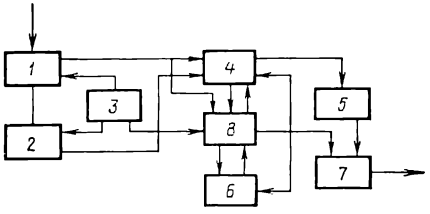


Fig. 1.5

Models. All the stages of development of control methods (Fig. 1.4) necessitate the building of models which provide a basis for formalization and mathematical description of the power industry as a large system of cybernetic type. Any model, which is an analytical instrument aimed at the attainment of a certain goal, cannot be a completely adequate replica of the studied object, i.e. a power system. Thus, all major types of existing and future models should be viewed in the light of this approach.

Future investigations must take into account representation forms of source data, which may be deterministic, partially probabilistic, incomplete, or uncertain, so as to determine the specific advantages of each form. However, practically useful model will be a combined model into which the necessary combinations of the above qualities of source data will be incorporated. The results of preliminary investigations show that the concept of a "grey" box, which has not been used yet in the field may be taken as a basis for the building of such a model. This concept provides a most practical approach to the investigation into a global system which interacts with the UPG. We maintain that a grey box, a thing that represents this global system and links connecting it to certain subsystems (biosphere, social and demographic factors, etc.), comprises a number of "black" boxes each representing certain subsystems whose interconnections are assumed to be of known nature; as a result, the system as a whole appears to be semitransparent, and the name grey box is used for this reason. In building the described model, account should be taken of the variability of all parameters of the system being modelled, including those which are taken as deterministic. Note that the parameters tend to vary when influenced by random disturbances

occurring within the system and also by the control actions available from the system control section.

Owing to the variability of system parameters and changes in *a priori* information about the operating power system, the model becomes obsolete soon. Thus it must keep up with the changing conditions. The model can be given adapting properties by using variable structures in it. In this connection, it should also be noted that modern computers of the third and fourth generations available to the power industry are capable of carrying out the synthesis of subsystem models by automatic changing their performance characteristics in response to their environment so that unalterable *a priori* information is not the only basis for handling the situation.

To illustrate one of the practical approaches to the situation described above, let us consider a regression model. To build such a model, we must find a linear approximation of it which is given by the following equation

$$y = \mathbf{A}U + \bar{B}$$

where **A** is the matrix of regression coefficients, and $\bar{B}$ is the vector of additional variables.

Given N statistical relationships characteristic of the values of control actions U and of their respective estimates y, one has objective function J

$$J = F(\mathbf{A}U + \bar{B})$$

The system optimality criterion is determined from the extremum of functional J found for the real values of regression coefficients, with numerous constraints imposed on the control coordinates.

Since *a priori* information is liable to become obsolete, the solution to the optimization problem, when obtained on the basis of it, is not optimal in practice. The properties of the controllable object and the characteristics of its particular components are varying in response to environmental effects and changes in the object structure. This requires that models be developed which would have their adapting properties allowing them to keep up with changing operating conditions of the power system. Self-adaptation can be effected by influencing the regression coefficients provided data on their values are available. An optimum model of the system is realized by computing the gradient of the objective function, the regression coefficients being estimated. This method of building a global model will require approbation based on natural or physical-model experiments.

Naturally, the above considerations concern the results of preliminary investigations, which would allow for building practical models. Such models would call for operating control of the UPG treated as a complex cybernetic system. According to the literature, there are practically no developments which would deal with the entire control

problem connected with such systems; we mean that in this connection account should be taken of the following: multiplicity of criteria concerned; a great number of inconsistent criteria (the problem of vectorial optimization); the uncertainty problem concerning incomplete information. All the facets should be dealt with by the analyst who treats the power industry as a subsystem having links of complex nature. Adequate solutions in the field can be found by employing modern computers and the ergaticity approach described above.

Transient processes and post-fault operating conditions. It is right to connect the urgent problems involved in power system control automation, including the algorithmization problem, with the study of normal operating conditions. The credible contingencies and their associated transients should be dealt with in this case through the use of a specific loss function. However, the growth and expansion of the UPG and the necessity of increasing its reliability require that standardized reliability factors be introduced which could depict, on an integral scale, loss indicators. In addition, methods that determine survivability —a new concept as applied to power system reliability—should be investigated.

A very important task to be tackled by researchers is the automation of optimization control of transient phenomena and, as a consequence, the automation of transient analysis. Unlike the existing control means that are based on a rigid control algorithm, future control devices, both automatic and cybernetic, would employ a flexible control algorithm which could adapt itself automatically to changes in power system operation. This can be done by changing the algorithm structure, adjustment coefficients, and control functions.

The future systems automation means, as assessed in terms of the methods for design and implementation, would be visualized in the form of devices capable of performing preventive work to resist contingencies, or at least capable of correcting the emergency conditions being created in order to lessen their severity. Thus, the methods of investigation into transient phenomena would be varied correspondingly.

The modern research practice is tending toward a refinement of computation methods and techniques with which a great variety of influential factors (such as increases in the number of electric stations, load centres, different events, etc.) would be taken into account, when finding optimum solutions on the basis of fixed initial parameters. Within the scope of these problems, some workers try to obtain solutions with an increased accuracy, as provided by computational mathematics, irrespective of the real engineering core of the tasks being handled. Such refinements, however, are mere abstractions since the source information is stochastic and incomplete in many cases, and the state variables tend to change in emer-

gency conditions, or the system automatic control equipment is being interfered with.

Thus, we may conclude that the further research work in the field should basically produce methods that would help to discover and realize those operative control actions which the new emergency control automatic means could output in order to change system operating conditions in the desired fashion, while the attempts to increase the accuracy of computations should be given less attention. With the old approach, the problem was expressed mathematically as follows

$$x = f(t, \Delta P_0, P_1, P_2, \ldots, P_k)$$

where ΔP_0 is the disturbance, and $P_1, \ldots, P_k$ are the given parameters of a fixed magnitude. The new approach may be based on the following formula

$$x = f[t, \Delta P_0, \ldots, \Delta P_i(t)]$$

where $\Delta P_i(t)$ is the parameter used to depict control actions provided by power system control equipment capable of adapting itself to the environment in the course of the process, and $P_0(t)$ are stochastic parameters.

At present, the new approach has found a few uses in the designing of power system control equipment intended to control asynchronous conditions and resynchronization (resultant stability) and also for computation of transient stability providing stochastic assessment of the obtained results. To attain optimum power system operating conditions, it is essential to have coordinated control actions in different channels and adaptation of the settings of protection means, regulators and emergency control schemes.

It follows from the foregoing that, when being chosen, new regulating devices must have a variable structure. They must respond to various states of system and to their control actions (which have concurrent and coordinated effects on the generator's excitation, turbine's torque, reactive power sources, load resistors, etc.).

To establish well-arranged and reliable criteria characteristic of emergency and post-fault conditions existing in a power system and capable of determining their severity rates, it is necessary in the first place to build models of a complex power system, which can describe its behaviour during transients. Again, the grey box concept would seem to be a useful basis for such models since it allows the connections between individual subsystems to be discovered, while treating the subsystems as objects separated from the system under consideration on the basis of their input-output, i.e. as black boxes. There are some particular realizations of this idea such as equivalent representation techniques, diakoptics method suggested by

Kron, and especially cybernetic modelling which takes into account stochastic properties of the system being investigated.

The above mentioned problems can be solved by modelling the processes of interest on compressed (accelerated) time scale. Given the model time decreased by a factor of 20 to 30 in comparison with the real process time, the researcher is able to automatically "scan" possible emergency conditions caused by different continuous active effects. It now seems that cybernetic and compressed time modelling will be combined in the future.

The described methods dealing with the analysis of and intense intervention in the processes, that run in a power system, should be provided with adequate power system reliability and survivability criteria which determine the quality of transient phenomena. In the case of automated control, the quality of processes that run in the UPG cannot be determined by the criteria usually employed as optimum ones in the theory of automatic control. The features of the UPG, which is a unique system, necessitate specific optimization criteria for both normal operating conditions and transient processes. It would appear that the latter should require integrated optimization criteria. Their application should not be limited to a particular process, rather involve all processes existing in a system. This allows the researcher to assess the overall influence of all the processes and their resulting effects concerning system survivability and the required standard and reliability of supply.

It seems evident that the years to come will see a drastic increase in the significance of power system management and control, since power generation is steadily growing, all types of power supply networks are expanding over tremendously large territories, and many social and economic factors as well as environmental effects are resulting from the power industry. In such circumstances, power systems expansion and operating control problems should be treated as a single multi-faceted problem.

With this approach, however, there may be differences between the analysis methods used, especially in the initial stage of the development of the united automatic power control system devised to exercise control over the power industry as a whole. Such system should include an automated data acquisition and processing system intended to solve expansion planning and forecasting problems connected with the power industry treated as an entity including a number of large systems. Such large systems may be assumed to be subsystems of a global super-system known under the name "biosphere-human society-national economy".

The development of the automatic power control system is following different lines. Over the period from 1971 to 1975, the computers employed by the system performed the function of the control engineer's consulting devices. In the years of 1975-1980, they

were given partially the dispatch control functions. The plans for the period from 1980 to 2000 envisage use of computers as devices with fully closed loop control. This will enable eventually a power system to grow into a cybernetic system, and management and control functions will be performed on an optimum and purposeful basis. It is important to stress that human effort must be involved in all stages of development in order to solve algorithmization problems; this means that management and control activities should be based on the ergaticity principle. Power system management and control will be effected in the future on a global basis, including such controllable objects as the UPG and pan-energy system, as well as international power pools.

Power system control and planning tasks are chiefly dealt with at present so as to provide for the production of a maximum amount of fuel and power at a minimum cost. In this respect a very important problem arises: harmful effects of the power industry on the biosphere should be kept at a minimum. We expect that present-day optimization methods concerned with power system operation should be developed to such a level where account is taken not only of such critical factors as fuel rates and discounted costs, but also of a combined comprehensive effect which includes the impact of the power industry on the biosphere. It seems evident now that this approach is applicable already to the development of the automatic power control system.

In a more distant period covering the years of 1990-2000, the need for the protection of geophysical state of the globe will require an adjustment of the production of all forms of energy. According to a number of investigations, which are void, however, of sufficient quantitative evidence, the earth's present geophysical state may be disturbed should the production of energy reach a certain "high" level. The solution to the problem is likely to require the development of new and unusual methods of investigation and comprehensive practical computation techniques to be used in such spheres as technology, economics, biosphere and geophysics. Of great importance, here, is the training of engineers and research workers who must acquire knowledge in the subjects concerned.

As to scientific-technological aspects, the problem requires that mathematical theory and practical methods of integrated optimization of comparatively complex systems be created. Also, important to the problem are planning and forecasting in conditions when design data are incomplete and represented in a stochastic and statistical form. The concept of information itself as applied to power engineering should be defined more accurately in terms of its specific features.

It would appear that the associated tasks should be tackled on the basis of a spatial-temporal system hierarchy by analysing changes

that are likely to affect the coordinated and interdependent structure of the particular hierarchy levels. Attention should be focused on the development of adequate mathematical models, linear and nonlinear, information models and also estimation and branching models which may be sometimes encountered in modern practice. It seems evident, however, that a most critical and forward-looking approach is the development of the theory of integrated (multiparameter) optimization which would encompass a great variety of problems concerned with harmful effects of the UPG and power industry as a whole, treated as a large system, on the interrelated subsystems constituting part of a global system "biosphere-man-technology".

Of utmost importance is the reliability of channels through which source and control data are transmitted. In the light of the tasks to be tackled at the higher levels of command hierarchy of the automatic power control system special attention should be paid to the development of new methods and devices used to control the servomechanisms installed at electric stations and substations and other types of equipment. Since human physical effort directly involved in the control of units and installations is continuously decreasing, the control equipment should be modified substantially in order to meet the specific requirements of automatic control.

The theory and practical methods of industrial psychology are critical in developing a network of computer centres for the automatic power control system, distributed over the country's territory, including such problems as the design and siting of such centres and providing communications links between them and the users. The automated dispatch control system (ADCS) uses various computers—digital, analogous, and hybrid, the operational capabilities of the latter type being considered worth-while. The computing, mixed computing/control and control functions performed by these machines must be top-level. Finally, adequate display means are necessary for the data produced and handled by the ADCS.

REVIEW QUESTIONS

1. What links exist between the fuel-and-energy complex and the branches of the national economy?
2. Describe the cybernetic principles underlying the fulfilment of tasks concerned with power industry.
3. What differences and similarities would you mention when describing the tasks concerned with power system expansion and operation control?
4. Describe the optimization methods and criteria applicable to power system expansion and operation control.
5. Draw the essential features of the objective function as is used in connection with power system management and control.
6. Describe major stages of development of power system management and control.

7. What are the preferable ways of working out the policy that helps to maintain power system operating conditions and provide for power system expansion?
8. Describe the ergaticity principle as applied to power system management and control.
9. What types of models are used by research workers investigating power systems?
10. Describe regression models and methods of their usage.
11. Describe the tasks concerned with integrated optimization of power systems.
12. What are major trends in automation of power systems?
13. Describe the electrical energy requirements as related to different users. Explain why these requirements are to be taken into account when analysing power system expansion and operation control problems.
14. Why is it necessary to change the forms in which power system management and control functions are implemented?
15. Describe the methods with which power industry-oriented information is obtained and converted. State the most important problems to be solved in the field.

Chapter 2

Power System Management and Control

2.1. General

The essential problem of the operation of a system comprising generating stations, networks, substations and consumers is how best to transmit power to the consumers and allocate generation among the stations. It is the responsibility of the control engineers to carry out the desired calculations and select the set points required in the event. These operations must be fulfilled on a nearly continuous basis. The basic aim of dispatching is to achieve minimum generation cost so that the following requirements are met: (1) satisfactory quality of supply; (2) observance of commitments to external systems, e.g. constancy of transfers and contribution to spinning reserve; and (3) maintenance of acceptable voltages under normal and emergency conditions.

The requirements above can be implemented by control over those links which connect the generation cost and the variables of load flows on the distribution networks with the frequency control mechanism. This involves such important aspects as calculation and regulation of the quantities of interest.

By dispatch control is meant centralized real-time control of the operation of stations and electric and thermal networks interconnected with one another and maintained in identical operating conditions so as to provide for a continuous electrical energy and thermal power generation, conversion and distribution.

The power system dispatch control system (PSDCS) exercises continuous control over the joint operation of all power installations of a power system in order to supply consumers on a secure basis with electrical energy and thermal power of the required quality, which is assessed in terms of frequency and voltage existing on electric networks and of pressure and temperature of steam and water delivered by thermal networks. In addition, the PSDCS provides reliability of service of a power system as a whole, taking into account economic considerations.

The PSDCS is a system in which many hierarchical levels interact with one another on the strict subordination principle. In countries with nationalized power industry, say, in the Soviet Union, England or France, the highest control level is nation-wide followed by the levels of power systems, plants and networks. In the USA and some other countries, where power industry is not under public ownership, no nation-wide dispatch control is usually effected.

The Soviet Union has a most advanced PSDCS and the Central Control Department (CCD) of the USSR United Power Grid (UPG) performs the functions of the highest, nation-wide, level of the command hierarchy, and has therefore control over all interconnected systems in the country. Thus, the orders of the control engineers at higher levels are fulfilled by the attending personnel at lower levels. In Soviet practice, plant as well as protective relay equipment, automatic control schemes and communications facilities may be under either direct or co-ordinate control exercised by the control engineer at a given level of the command hierarchy.

Under direct control of the control engineer of a given level of the command hierarchy are plant and automatic equipment which require the adjustment of the activities of the attending personnel at the lower levels or the joint operation of relay protection and automatic control schemes belonging to several controllable objects. These control actions are performed in this case merely in accordance with the orders issued by the control engineer of the given level of the command hierarchy.

Under co-ordinate control of the control engineer of a given level of the command hierarchy are plant and automatic equipment whose status and operating conditions influence considerably the available power, plant reserve capacity and performance of the whole grid and also the operating conditions and reliability of electric networks. In this case, the attending personnel of the lower levels perform control actions independently following instructions from the control engineer of the higher level of the command hierarchy.

Maintenance of protective relays, automatic control devices and communication facilities of major plant of a power system requires special orders be submitted to the approval of the respective PSDCS body. The equipment may be removed from (even if the approved report is available) or placed in service, or the major network structure can be altered only under directions or with the knowledge of the control engineer in charge.

The control centers are equipped with communications, telemetering, automatic control and computer-based facilities that enable the control engineers to implement the monitoring and control

actions. The connections and operating conditions of major network and plant are represented by a wall mimic diagram and also displayed on control desks by using telemetering and remote signaling devices and CRT display units.

The control centers communicate with the controlled objects through unswitched channels operated on back-up basis.

The growth and expansion of power systems requires that more complex tasks be accomplished by the PSDCS. This necessitates the entirely new means and methods of operational control. An approach to the situation is the development of automated dispatch control systems (ADCS's). The ADCS is a united complex of dispatch control and computer facilities, which provides for automated gathering, transmission, processing and presentation of real-time data on the connections and operating conditions of a power system, and makes it possible to carry out calculations necessary for maintaining and planning optimum operating conditions.

Computers produce a great deal of telemetered and statistical data of greater validity and present them selectively to the control engineers using CRT display units. The latter can display the connections of the individual power installations, the actual values of power, voltage or any other variable, and also the variable deviations.

Planning the optimum conditions on the basis of computerized calculations and presentation of the calculation results on CRT display units improve the quality and effectiveness of overall system control. As a result, optimum economy of energy resources is achieved, incremental fuel cost for thermal plants is reduced, and a maximum hydro generation is ensured, taking into account the demand of all water users.

The development of ADCS's leads to a higher level of automation of the important power system control functions. Present-day computer involvement in power system operation concerns load frequency control. Further use of computers is related to emergency automatic systems for control of fault spread and isolation.

2.2. Primary, Secondary and Tertiary Regulation

The basic requirement is that energy input to boilers and prime movers should equal the energy supplied to consumers plus system losses. Note that under these circumstances the consumers are supplied with sufficient amount of energy of satisfactory quality. This generation-demand balance is achieved through the use of automatic controls on boilers, which regulate the energy flow (i.e. steam mass and pressure) into turbines (Fig. 2.1).

The regulation obtained by a speed-responsive governing system (SRGS) is called the *primary regulation*. The average power output

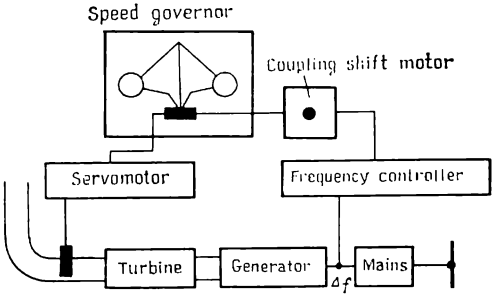


Fig. 2.1

of the turbine is varied by adjustment of the SRGS setting through a speeder motor. Pulses applied to the speeder motor to raise or lower the turbine output can be initiated manually or, as in many modern systems, automatically by a signal dependent on the frequency deviation Δf (Fig. 2.1). This is called the *secondary regulation.*

Economic dispatch, providing generation loading for minimum cost, is obtained when instructions from a load scheduler to the governor are realized in accordance with the incremental costs of various generating units. Working out the instructions that meet the demands of economics is called the *tertiary regulation.* Constraints on the distribution of generation imposed by network capability or environmental factors may be included in economic dispatch calculations.

Operation of interconnected areas. Change in the operating state of one area will affect all other interconnected areas. This is particularly so when the generation-demand balance is upset. If an undertaking generating 10% of the instantaneous power of an interconnection suddenly lost 500 MW, governor action throughout the interconnection would cause nearly 450 MW to be picked up externally and only 50 MW internally to the undertaking. This position would persist for some seconds until modified by secondary regulation.

Frequency-bias-tie-line control is commonly used for this. The underlying principles are that each area should normally adjust generation to meet all changes in the power-demand balance within its boundaries and that each area in which an unbalance does occur should be assisted by the remainder of the interconnection until its balance is restored.

Changes in the common frequency or in inter-area (tie-line) power flows are indications that imbalances exist and "area regulation signals" containing both terms are used to determine necessary generation adjustments. Thus required generation change in area A

$$\Delta p_A = k\,(f_1 - f_2) + (p_{1A} - p_{2A}) \qquad (2.1)$$

where f_1, f_2 and p_{1A}, p_{2A} are required and measured values of frequency and external power transfers to A, respectively.

The value of k will be some 2-3% of area generation per 1 Hz. The generation changes within each area will be dispatched manually or automatically from its control center to individual stations and generators, in accordance with incremental cost and response criteria.

Inter-area transfers. The procedure for calculating the power transfers will depend on the size and organization of undertakings. If these are autonomous, with no central control, following exchange of incremental costs undertakings will purchase energy which is available from neighbours at a cheaper price than from internal generation. The transfers, agreed perhaps 30 minutes in advance for a like period, will probably be small compared with the undertakings capacities; security will be assessed individually with limited representation of neighbours, but with an agreed spare contribution. If a "coordinating control" center exists an iterative sequence may be used:

1. The coordinating center makes an estimate of individual area transfers, based on the immediate past adjusted for known changes in plant availability and demand, and passes these to the areas;
2. Each area calculates a generation schedule for this transfer plus its expected demand. The costs of varying the area generation and hence the transfer about the given figure are returned to the coordinating center;
3. These incremental/decremental costs are compared at the coordinating center, a second estimate of transfers made; and if justified the process repeated from step 2. The cycle may be repeated, several times over a few days interleaved with security assessment studies to confirm the acceptability of the resulting network flows.

Omitting security checks, worth-while transfer changes will result from area generation increments Δg_{An} at cost $\Delta\rho_{An}$ and decrements Δg^{Bm} at saving ρ^{Bm} for the nth and mth changes per area, respectively, such that

$$\rho_{An} < \rho^{Bm} \quad \text{and} \quad \sum_A \sum_n \Delta g_{An} = \sum_B \sum_m \Delta g^{Bm} \tag{2.2}$$

Listing the ρ_{An} in ascending and the ρ^{Bm} in descending cost orders, the answer is easily obtained by pairing increments and decrements down the lists, carrying differences forward (i.e. if, say, the first increment is cheaper and also larger than the first decrement, the increment surplus from the first pairing is matched against the second decrement and so on). Restricted transmission capability, expressed by group constraints, can be included by keeping running totals of remaining constraint margins as increments and decrements are paired.

Detailed security analysis with the computation would require load-flow analysis (which will be described later). Transmission losses can be allowed by weighting the costs by loss factors derived from previous studies or by load flow within the calculation.

2.3. Automatic Control of Power System in Normal State of Operation

The state variables of a power system in normal operating conditions can be controlled manually. At present, however, there is a tendency to replace manual control with automatic control. This is achieved by developing automatic systems which could control power systems in normal operating conditions, taking account of their basic characteristic features such as the impossibility of storing the end-product and the necessity of continuously matching generation and demand.

Automatics of normal state of operation has received a large development effort and is now characterized by the diversity of forms and types closely linked with various types of the controllable objects such as power systems and their interconnections. Such systems may be approached not only from an engineering but also from economic and even from organizational angle. Thus the automatic control of systems in normal state of operation may play either supplementary or main part in dispatch control depending on the types of power systems, transmission capabilities and on the level of coordination concerned with power exchanges.

This applies to all types of control, and mainly to automatic control of frequency and active power described in this section. Such facilities may be comparatively sophisticated devices which form in this case an automatic generation control system (AGCS). The term "automatic load frequency control" (ALFC) is also often used to identify this problem area, which usually involves control of stations, power systems and their interconnections. To discuss the ALFC systems, consideration first should be given to a single unit working into an isolated load, the case which is now considered as an almost hypothetical one.

When the generator load changes adjusted should be the position of the control valves of a steam turbine or of the opening of the gates of a hydroturbine.

A control system responds to a variation of the rotational speed* of the unit, caused by an imbalance of its generation by changing the input of the working fluid (water or steam) to the turbine and restoring the balance between the turbine output and unit generation. Any automatic control system uses two types of control: isochronous

* Hereafter referred to as "speed".

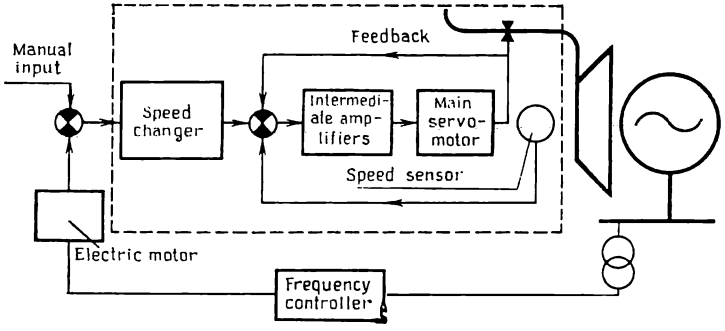


Fig. 2.2

(integral) and proportional. In isochronous control, the controlled quantity (speed or frequency) returns to its value before the disturbance, say, f_0; and in proportional control to the value given by

$$f = f_0 - \Delta P\sigma \qquad (2.3)$$

where ΔP is the unit generation change and σ is the speed regulation*, which is the reciprocal of the gain of the control system, K_g.

It is obvious that isochronous control provides for the highest, in terms of frequency, quality of electric energy produced by the unit. But even in the simplest case under consideration concerned with a single disturbance, isochronous control is difficult to implement, because the automatic control requires many trade-offs to match fast response and stability of the system.

In steam turbines, many small time lags of similar duration in speed-governing systems affect the process of control; in hydroturbines, this is affected by a hydraulic impact in the penstock with the result that a positive feedback is established. In the circumstances, with great K_g values, the control system should be given a time delay in order to prevent swings in the system and ensure stability. The greater K_g, the higher is the accuracy of frequency control in a steady state. Thus a slower mode of operation is required, this tends to impair the quality of frequency control in a transient state.

With $\sigma = 0$, the control becomes isochronous, most vulnerable to the above impairment. Therefore, a "pure" isochronous control is not applicable in practice, and a combined type of control, isochronous plus proportional, is a convenient way-out.

Figure 2.2 shows a block diagram of an ALFC system for a single unit.

---

* The exact relationship between σ and K_g is given by $K_g = (1 - \sigma)/\sigma$. In most cases, we have $\sigma \ll 1$, which gives $K_g \approx 1/\sigma$.

Proportional control is effected in the speed-governing system itself, which comprises a servomotor(s) to alter the position of the turbine control elements, a controlled variable (speed or frequency), sensor, and a number of intermediate amplifiers. Modern turbines usually employ hydraulic servomotors, while steam and electric servomotors are being under development. As to speed sensors and intermediate amplifiers, there is a tendency to replace mechanical devices with hydraulic and further with electric ones.

The function of isochronous control is performed by an autonomous device not included in the speed-governing system but acting on it by virtue of a speed changer (SC). The latter is used to change the speed governor setting according to the changes in f_0 sensed by the frequency controller.

The fashion in which the frequency controller influences the speed governor depends on the type of connection between the two devices. As a rule, they are connected via an electric motor, which receives control pulses from the frequency controller and thus alters the position of the element that determines the value of f_0. Since an electric motor is an integrating element, the system possesses the astatism of first order even if devoid of any other integrating elements. It seems evident that other types of connection being developed must result in the same behaviour of the system.

It is the proportional-control, fast, section of the complex "speed governor-frequency controller-speed changer" which responds to a change in the unit generation. Thus the functions performed by this section are known as primary regulation. The latter resists considerable frequency deviation in a transient state; but to provide for adequate response time and stability gains for the primary regulation loop should be chosen in the range of 20 to 30, which corresponds to a speed regulation of 3 to 5%. It follows from (2.3) that there is a large residual frequency deviation, Δf, in a steady state, which is called the frequency offset. It can be generally eliminated with the help of the tie-line and frequency controllers (secondary regulation).

Thus, the discussion above outlines in general terms how a desired quality of generation is achieved in the case of an isolated unit. The steps outlined are practically the same for several units and even for several stations provided they are interconnected via stiff lines which means that there exists a concentrated power system. If this is not so, a change in system load is accompanied by electromechanical transients, which are relatively complicated phenomena.

To illustrate, consider a node (Fig. 2.3*a*) having its own sources shown in the figure as generator *G*1. The node is coupled via a transmission line to a remote electric power station *G*2 having no consumers. Assume that the turbines of *G*1 and *G*2 are fitted with speed governors, which means that primary regulation takes place and no

secondary regulation is effected. Under the circumstances, it is the attending personnel who alters the speed governor settings in order to keep the frequency within the prescribed limits and eliminate the frequency offset, thereby performing the functions assigned to the secondary regulator.

Let us assume that the total system load experiences a change (increase) by the magnitude ΔP_n, which is related to the total nominal output power of the two generators. The aim is to find how this change will be distributed between the generators involved in parallel operation. First the distribution is inversely proportional to the electrical distance from the generator to the load. As a result, nearly all magnitude of ΔP_1 is lodged at that moment in $G1$, with the result that its speed falls. Only a change in rotor angle δ causes $G2$ to be loaded; its speed falls too provided that the transient stability condition is satisfied. The processes that occur in a two-unit system during a load swing are illustrated in Fig. 2.3*b*, *c*.

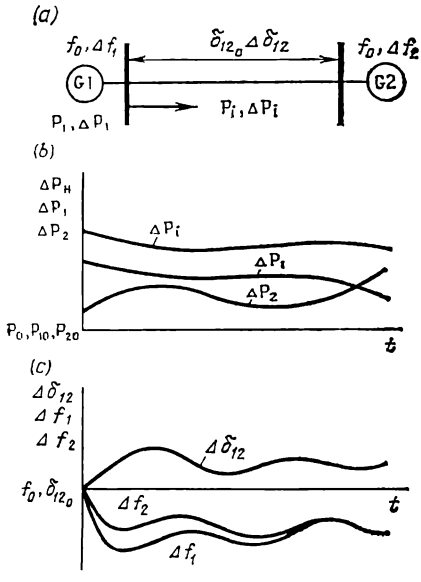


Fig. 2.3

The change in speed is sensed by the speed governors which operate to change the position of the controls. If the speed regulations σ of the regulating units related to their nominal output powers are equal to each other, then an extra load ΔP will be allocated among them in proportion to the values of these powers. The system frequency, however, will no longer be at its scheduled value due to the fact that frequency offset Δf is present. The latter should be eliminated by the actions of the personnel or with the help of the secondary regulators, if any. This is described in detail in textbooks on atomated power system control. In our discussion, it is important to stress that this can be done by varying generation at the two units either proportionally or nonproportionally when only one unit, say, $G1$ is subject to corrective action.

The latter case, as a most important one, requires a special consideration. In a complex system, it follows from (2.1) and Fig. 2.3 that influencing the speed changer of one of the generators to restore the scheduled value of the system frequency gives the desired effect and also provides for re-allocation of the extra load shared by them

during primary regulation. The use of proportional-integral control in modern power systems allows one to respond quickly to the changes in load and distribute it between those units which are selected specifically for the purpose.

Thus the secondary regulation can be used to redistribute the load changes. Now consideration should be given to the criteria of the secondary regulation. The process should be treated both from technical and from economic standpoints. Furthermore, in parallel operation of individual electric stations, power systems and their interconnections power may be exchanged in two ways.

The first method is characteristic of the power systems of the Soviet Union and other countries with nationalized power industry, including all socialist countries and some large capitalist countries (England, France and, to some extent, Japan). In these countries, power exchange between the various parts of the interconnections mainly depends on economic considerations and the magnitudes of the power flows through the tie-lines are determined by a nonfixed programme (the so-called free tie-line power flow mode). This determines in a strict way the requirements imposed on the secondary regulation systems which serve to maintain the scheduled value of system frequency (that is to eliminate the residual frequency deviation) and provide for economic dispatch of generation depending on the characteristics of units operating in parallel.

The second method applies to the power systems of the countries in which individual power utilities are available, including the USA, Federal Republic of Germany and some others. Though developed electric networks exist there, the magnitudes of the interchange flows through the tie lines are determined by a fixed programme in accordance with the contractual agreements into which enter the various utilities, either private or public. Here the secondary regulation systems are the means for implementing such agreements. Indeed, they are not basically designed to compensate for the residual frequency deviation introduced by the speed governors and perform the economic dispatch function; preferably, these systems are used to maintain at a prescribed value the tie-line power exchanges between the various utilities. This type of system control is called the tie-line bias control.

The secondary regulation systems were intended to solve different problems in different conditions, which determined eventually the trends of their development and improvement. The systems devised for the first method played the supplementary part and did not influence considerably the behaviour of the power systems under control. On the other hand, the systems developed for the second method were always considered as the principal control elements; thus a great deal of attention has been given to their design so as to obtain well-engineered and operationally reliable devices.

Not only technical but also organizational problems are important in the design and operation of the secondary regulation systems. Another critical point in this connection is that the systems of the both types tend to acquire more resemblant features.

In the early stages of control development, in the case of free tie-line power flows the frequency control was the main task of automatic control devices of power systems in normal state of operation. This arose from that the size of the power systems was relatively small and even a small change in load resulted in a large frequency deviation. For example, frequency variation in a power system with large electrometallurgical undertakings, integrated chemical plants and electric transport facilities as consumers reached 0.2 Hz or even 0.5 Hz at certain moments of time. Though in this case it was necessary to change load only for one station or even one unit, manual control was difficult to implement and its quality was naturally bad.

At that time many researchers were thus entrusted to work out automatic devices which would perform the necessary corrective actions for which the attending personnel is usually responsible. This work was carried out under complicated conditions: the rigorous requirements on sensitivity, stability and reliability of the systems could not be met since the appropriate technical means were practically unavailable. Nevertheless, some organizations, including the Lenenergo Central Laboratories in the Soviet Union and Leeds & Northrup Companies in the USA, developed the prototypes of the controllers which operated for a certain period of time at several electric stations. The work took, however, such a long period of time, that by the end of it, a qualitative change in the nature of the controllable objects necessitated new requirements for the frequency controllers.

In fact, the first control devices, though cumbersome and imperfect, were available in the 1930s. The advent of new automatic control elements such as magnetic and rotary amplifiers at the end of the 1940s and the beginning of the 1950s made it possible to realize in practice the above requirements. By that time, however, the networks connecting individual stations and systems had been united. As a result, the level of the power swings in an interconnection decreased considerably with respect to the available unit generation, and the respective frequency variation drastically reduced down to several hundredths of hertz.

Thus the role of the frequency controllers in the power systems with free tie-line power flows changed completely: they were transformed from the principal control elements indispensable for power system operation into supplementary control elements. Nonetheless, the necessity of maintaining power systems in normal state of operation made the power engineers search for the optimum allocation of

generation among the units, stations and systems operating in parallel. This problem which is considered up to now an important one is called the economic dispatching.

Historically, the economic dispatching arose from that the units have different economic characteristics (assessed in terms of incremental costs) and different electrical distances from the load centres. The problem is generally solved at the stage of power system operation planning (when scheduling, in particular, daily load patterns). Since the load is a random value, its planning and scheduling are based on estimation and forecasting. As is evident, the accuracy of estimation is not absolute and in operational control, there appear the so-called unplanned load deviations; this requires additional redistribution of load among stations and systems in order to reach optimal performance of the system. This is carried out by tertiary regulation or economic dispatching in which the speed changers of the units are adjusted, as in the case of frequency control. We can utilize for tertiary regulation most of the technical means for frequency control. Thus economic dispatching has been considered for many years as part of the functions performed by the LFC system.

To provide for economic dispatching, automatic control equipment should be fitted with devices capable of performing practically the same calculations as those involved in daily scheduling. Naturally, these devices should be operated at a high speed so as to ensure real-time calculations. The problem itself is simplified to some extent since forecasting is eliminated and data on the actual load flows in the system can be utilized, and so on. This caused (when possible) the elimination of short-term planning and transfer to the fully operational optimization of system operating conditions. The problem from the technical point of view, is rather complex, especially in the case of systems with free tie-line power flows.

Indeed, free interchange of power shows that no constraints are imposed on the optimization calculations which would cover, in the ideal case, all generation sources influencing in one way or another the economic operational characteristics of a power system, interconnection or even a united power grid. With this approach, however, the problem becomes too cumbersome and no practical solutions to it are available. A convenient way-out is to use some artificial techniques based on the hierarchical structure of the control system. Using these techniques, generation sources are collected together or the system is divided into several parts (problem decomposition). Nevertheless, the amount of computations is sufficiently large and stringent requirements are placed upon computers.

Further, the associated telemetering and communication equipment should be at a higher level. Since the optimization computations cover both the neighboring and distant sources, long data transmission channels are necessary, which can be operated

reliably only when special measures are taken. In addition, automatic control of the power output from large units requires that the unit-level control equipment, i.e. automatic devices mounted directly on the units, be well-engineered and operationally reliable devices. This is especially the case with the units installed at the thermal power plants; the number of the units is usually great and it is evident that poor operation of the automatic means mounted on different unit elements (say, boilers) would hinder rapid handling of signals from the LFC system.

We can see therefore that frequency control, when supplemented with a much more complex control task, economic dispatching, requires that many technical problems be solved with the direct participation of the specialists engaged in the design and operation of the LFC system. In countries with nationalized power industry, however, attention is always focused on the aspects concerned with primary and tertiary regulation. As a result, the LFC system as applied to the normal state of operation of a power system has not yet been developed there on a wide scale.

In countries with individual power companies, either private or public, the situation is quite different. The principle of non-intervention followed by the companies may be realized in the case of an interconnected electric power system merely by virtue of secondary regulation, on the basis of the following operation scheme. When a tie was established to link together two companies through a transmission line, a power interchange controller was installed on that line by each company. The controllers were operated in such a way that all load changes occurring within the companies were compensated for by their units, while the power flowing through the intersystem tie-lines was always kept constant and could be varied merely by readjusting the controller settings; in each specific case, this corrective action was carried out by bargaining between the dispatchers of the companies. Initially such controllers were installed directly at electric stations or at their neighboring substations. With subsequent increase in the number of tie-lines linking a given company with its neighbors and the power flowing through the tie-lines in different directions, one electric station could not provide for power exchange control and a number of generating sources at certain distances from one another were required for the purpose. The control equipment of such systems is installed at control centers or on facilities serving as their substitutes (say, on the control desks of the largest electric stations), while metering and control functions are performed remotely by telemetering/telecontrol systems.

When the power flows through different tie lines in different directions, it is impossible to implement its control using each tie-line separately. Here subject to control is the algebraic sum of the power interchanges received or supplied by the individual companies.

It is known as the area net interchange and is the main controllable variable of the given system. While maintaining the preset value of the area net interchange, the system simultaneously responds to the frequency deviation Δf. Assume that in normal state of operation of a power system its frequency is always kept at its nominal value. For a number of interconnected companies each of which maintains a certain value of the area net interchange the load on all tie-lines has a constant value predetermined by computation.

In accordance with the above discussion, let us now consider certain features that characterize power system operation in the case of controllable tie-line power flows whose magnitudes are determined by a fixed program. *The first feature, and a most important one*, consists in the fact that normal operation of interconnected network can be achieved without centralized dispatch control. There have been practical systems utilizing this method. In such systems, contingencies basically occur when system normal operation is disturbed. When no disturbances are present, normal operation is attained under the condition of a comparatively small transmission capacity of the tie-lines amounting to not more than 5-10% of generation available from system parts linked together by these lines. This type of operation is ensured, indeed, by secondary regulation.

Secondly, optimization calculations are simplified which may apply in this case to a comparatively small section of electric network, boundary conditions being specified for the ends of that section. Of course, these boundary conditions are not selected arbitrarily, but rather depend on the results of the calculations made in the stage of conclusion of buy-and-sell power interchange agreements between companies, i.e. during the system planning stage. Sometimes, the above conditions are specified during the stage of system operational control. Note, that in the case of the power systems with individual companies the conclusion of the buy-and-sell agreements is one of the main functions of control personnel.

However, the load-frequency control equipment is not usually employed for these calculations and is given the preset adjustment on the basis of the boundary conditions specified. As a result, a natural decomposition of the problem is achieved and simpler solutions are obtained.

Thirdly, with the controllable mode of operation, the procedure is simplified and aimed at finding the conditions which determine power exchange. This means that the value of interchange can be tied up automatically to the specific moments of time within 24-hour period, to the events that occur at the moment when power exchange takes place in different parts of a system, etc. It is known that these factors influence considerably the economic variables depicting system operation and, consequently, the cost of kilowatt interchange. Meter readings are, thus, insufficient to implement system control

properly and a complex computerized system is required in the case of free tie-line power flows. On the other hand, the controllable mode of operation does not necessitate such a system, an important feature in those stages of control development when no computers are available.

The last but by no means the least feature of the controllable mode of operation to be considered concerns a simplification of the automatic control equipment proper. In the case under consideration, this equipment is usually a local one designed to exercise control over comparatively small territories, and thus offers greater reliability. In addition, the fact that the equipment plays an important role in system operation ensures its careful maintenance, with the result that successful operation of the equipment is achieved in most cases. Thus, when supplemented with necessary technical facilities, this equipment can provide for solution of economic dispatch problem, which will be described later on.

In the early estimation of power engineers, the above features of the system with controllable tie-line power flows were considered to be advantageous, but this estimation underwent some changes with time. First of all, it turned out that interchange magnitudes can be handled according to a fixed program merely in the case where each company has a reserve margin sufficient to compensate for all short-term load changes directly within the region of their occurrence. If the reserve margin is small or distributed unevenly, i.e. one company has a greater and another a lower value of it, then the loads fixed on to their respective tie-lines for a long period of time do not allow these lines to operate effectively. This resulted in a modification of the structure of the load-frequency control equipment and the concept of area was, thus, introduced, thereby allowing power exchange computations to be performed within the boundaries of such *area of regulation.*

The term area appeared in the USA several decades ago. At that time, area boundaries mainly coincided with company boundaries and intersected the latter only in a few, most complicated, cases. The development of power industry, however, caused drastical changes in the situation. In the early stages of this process, there existed imperfect technical means of load-frequency control equipment which covered large territories with great difficulties, while big companies were provided, each, with a number of areas.

At present, the enlargement of areas takes place on a wide scale. This mainly arises from the fact that control engineers try to utilize reserve margins to a more full extent. Under conditions of interconnected networks, the objective can be achieved due to both the benefits resulting from intersystem operation and the latitude effect, which consists in shifting the points in time when load maxima are obtained in different hour zones. Also, the extension of the opera-

tional capabilities of technical means incorporated in load-frequency control equipment is useful for the purpose.

A wide range of computers and pulse-code telecontrol facilities are now available to enhance load-frequency control equipment. As a result, many problems that could not be solved in the past are being handled with ease in the present time. This is concerned, for example, with economic dispatch problem. In particular, data are transmitted through long lines at a lower cost and with a higher fidelity. The buy-and-sell power exchange agreements characteristic of controllable mode of operation require more simple payment procedures, a feature important to countries with private power companies.

The above-mentioned factors resulted in certain changes in the power industry of countries with individual companies. In the United States an increase in the country's generating capacity between 1968 and 1973 was accompanied by a reduction in the number of areas from 300 to 120. The enlarged areas help to form interconnections of the first level known as *power pools*. A pool comprises a number of power companies which enter into buy-and-sell power exchange agreements to be fulfilled both under normal and emergency conditions according to the appropriate payment procedures. If the pool boundaries coincide with the area boundaries, then the companies within the pool utilize free tie-line power flow mode and gain by that. Computers are employed to calculate payments in accordance with contractual agreements.

The free tie-line power flow mode is also applicable to *super-pools* which are interconnections of the second level, each of which comprises a number of neighboring pools. The pools and super-pools necessitate an elaborate form of dispatch control with accurately determined functions of control personnel. Thus there is a certain resemblance between the countries with the nationalized and the private power industry, the latter borrowing from the experience of the former.

It should be noted that the countries in which power industry is under public ownership may adopt certain organizational schemes characteristic of the countries with private utilities, i.e. some elements involved in area-based power systems. This is due to the fact that the publicly controlled industry comprises united power systems of a very large size and is faced, therefore, with a difficulty in handling economic dispatch problem. It seems doubtful to us that the problem can be solved without decomposition. As a result, proposals are made according to which controllable power flows should be carried out on the tie lines connecting individual regions, which also helps to tackle managerial control problems. In addition, it is standard practice to use a fixed program for the power flows on the tie lines that intersect the boundaries of different countries; even those cases will apply in which the both countries involved in power exchan-

ge have nationalized power industry. We can see that the above discussion concerns the both forms of power industry organization.

There are cases, which are mainly concerned with free tie-line power flows, where it is necessary to limit the magnitudes of such flows when they exceed their margins in terms of thermal, steady-state or dynamic stability. The solution of this particular problem should be found as part of the complete solution to all problems relating to automatic control equipment that ensures normal operation of the system.

Automatic control schemes for system operation can be classified into two groups: schemes providing for frequency control and economic dispatch and schemes dealing with frequency control and power exchange through weak tie-lines.

2.4. Economic Dispatch

Problem statement. The optimization problem associated with a daily pattern of a power system is formulated as follows: given operational constraints, we seek to find minimal fuel costs C (or total fuel rate ΣB) of production and distribution of power within the system. The function of C or ΣB is a nonlinear function of system operating conditions.

Subject to operational constraints are a set of controllable variables and functions thereof. The set includes loads on stations and network facilities, water consumption for hydro power plants, fuel rate for certain types of fuel for thermal power plants, etc. The constraints can be expressed in the form of equations which depict, for example, power balance for a system, or inequations which may deal with maximal or minimal magnitudes of station loads. There may be either linear constraints (say, those relating to power balance), or nonlinear constraints which may apply to fuel rate.

The following observations may be made concerning the optimization problem associated with a daily generation schedule of a power system:

(1) Multivariable nonlinear functions are employed to represent the problem;

(2) The variables and their functions are subject to a large number of constraints; and

(3) There are a set of solutions to the problem from which the best one should be chosen.

The optimization problem is in the scope of nonlinear programming methods. The problem complexity is high, since there are a large number of equations and real-time solutions are required.

Problem solution. The problem resolves to *the minimization of total fuel costs for each hour of a day*. The relationship between the operating conditions for different hours of a day, which depends on

the availability of hydro and thermal power plants with a limited fuel rate, is established by introducing Lagrangian multipliers. Note that an optimum generating mix is not involved in problem consideration. Optimum operating conditions providing for a minimum of total fuel costs are determined by

$$C = \sum_{i=0}^{n} c_i B_i \tag{2.4}$$

where c_i is the cost of one ton of equivalent fuel per hour for the i-th station, and B_i is the equivalent fuel rate per hour, $B_i = f(P_i)$.

We seek to find station loads P_i at which a minimum of function of C is obtained.

One can take account of power balance by considering a station with $i = 0$ as a slack bus. This gives a condition in which all station loads P_i ($i = 1, 2, \ldots, n$) except that of the slack bus are independent.

During the optimization process, station loads P_i and transmission line loads P_l are subject to the following constraints in the form of inequations

$$P_{i\,\min} \leqslant P_i \leqslant P_{i\,\max} \quad (i = 0, 1, \ldots, n) \tag{2.5a}$$

$$P_{l\,\min} \leqslant P_l \leqslant P_{l\,\max} \tag{2.5b}$$

The oprimization utilizes a modified gradient method.

The constraints as given by (2.5a), to which the independent variables P_i ($i = 1, \ldots, n$) are subject, are dealt with at each iteration by equating the variables, that exceed their permissible limits, with these limits. The constraints as given by (2.5a) and (2.5b) to which the dependent variables P_0 and P_l are subject, are dealt with by using penalty functions. Thus for a power system having thermal power plants only, the objective function will be

$$F = \sum_i c_i B_i + W_0 + \sum_l W_l \tag{2.6}$$

where W_0 is the penalty function introduced for P_0 when conditions according to (2.5) are disturbed, and W_l is the penalty function for l-th transmission line.

Optimum operating conditions are found when the partial derivatives of the objective function ($i = 1, \ldots, n$) are zero

$$a_i = \frac{\partial F}{\partial P_i} = \left(c_i b_i + \sum_i \frac{dW_l}{dP_l} K_{il}\right) - \left(c_0 b_0 + \frac{dW_0}{dP_0}\right)(1 - \sigma_i) \tag{2.7}$$

where $b_i = dB_i/dP_i$ is the incremental rate of consumption of energy carrier (equivalent fuel for thermal power plant, or water for hydro power plant), $K_{il} = \partial P_l/\partial P_i$ is the load allocation ratio for the i-th station as referred to the l-th transmission line, and $\sigma_i = \partial \pi/\partial P_i$

is the incremental transmission loss for real power in the network of the i-th station.

The magnitudes of incremental transmission loss σ_i and increments of loads P_l carried on transmission lines under consideration are computed during the iterative procedure depending on the values of real loads. Using the values of P_{ik}, the components of gradient vector a_i are determined.

The optimization step length is then calculated, i.e. the changes of the independent variables, ΔP_{ik}, are found by

$$\Delta P_{i,\,k+1} = -\mu_i H_k a_{ik} \tag{2.8}$$

where μ_i is a scale factor, and H_k is a constant.

During the next step of calculation, the following iteration is used to determine the values of $P_{i,\,k+1}$

$$P_{i,\,k+1} = P_{ik} + \Delta P_{i,\,k+1} \tag{2.9}$$

At each iteration, all variables are to be involved so that a condition given below is satisfied

$$| a_{ik} | \leqslant \varepsilon_a \tag{2.10}$$

where ε_a is a preset small quantity representing the permissible error.

Since the values of a_i experience a considerable change in the course of optimization, the constant H_k may vary automatically depending on the sign of the scalar product of gradient vectors in the adjacent iterations

$$\text{with } \sum_i a_{i,\,k+1} a_{ik} > 0 \text{ one has } H_{k+1} = \beta_1 H_k \tag{2.11}$$

$$\text{with } \sum_i a_{i,\,k+1} a_{ik} < 0 \text{ one has } H_{k+1} = \beta_2 H_k \tag{2.12}$$

where $\beta_1 > 1$ and $\beta_2 < 1$ are constants.

To improve the convergence of the optimization process, one can use, in addition to changing the value of H_k, a technique in which the sign of the objective function is taken into account in cases where that function reaches higher magnitudes in terms of modulus. This technique may be used in conjunction with a limitation of the modulus of penalty functions (penalty components) included in the values of a_i. This limitation allows one to maintain the difference between the values of a_i for the different variables.

As stated above, the constraints, taking the form of (2.5*a*) and (2.5*b*) and relating to dependent variables, are dealt with using the method of penalty functions. In this case, the penalty functions, included in the objective function as given by (2.6), are calculated by

$$W_j = 0.5\alpha (P_j - \bar{P}_j)^2 = 0.5\alpha\rho_j^2 \tag{2.13}$$

where α is a given factor, $\overline{P}_j$ is the permissible load variation, and ρ_j is a factor representing constraint limit deviation.

The above approach is disadvantageous when the solution is at the boundary of the permissible region, which results inevitably in constraint limit deviation. One can make the value of ρ_j as small as desired by increasing the value of α in (2.13). However, this causes a considerable decrease in the rate of convergence of optimization process.

There is a modification of the described method including the steps as follows: if the convergence for the permissible load variation $\overline{P}_j$ is characterized by the deviation ρ_{j1} in the case of calculations with small values of α, then a new optimization step is carried out in which the derivative of the penalty function is computed by

$$\partial W_j/\partial P_i = (\overline{W}_0 + \alpha\rho_j)\,\partial P_j/\partial P_i \tag{2.14}$$

where

$$\overline{W}_0 = \alpha\rho_{j1} \tag{2.15}$$

If, on completion of the new optimization step, the convergence is characterized by the deviation ρ_{j2}, then the values W_0 and $\alpha\rho_{j2}$ are added together, and still another optimization step is performed.

Optimization steps are then repeated in a similar way until the following condition is satisfied in terms of all variables

$$|\rho_j| \leqslant \varepsilon_\rho \tag{2.16}$$

where ε_ρ is a preset small quantity.

The computer-based programs according to the method are used on a large scale.

2.5. Control of Normal Operation of Power Systems with Free Tie-Line Power Flows

Primary regulation plays a main role to system control in a power system with free tie-line power flows in terms of matching generation to load demand and utilizes for the purpose speed governors of turbine units. A rapid secondary regulation basically provides for a limitation of power in accordance with line transmission capability. Economic dispatch is obtained by virtue of a more slower tertiary regulation. The functions of the latter are often performed manually by operating personnel in accordance with instructions issued by a control engineer who tries to reallocate among the units those loads which have been picked up by them during the primary regulation, thereby providing for optimum operating conditions of the entire system.

Primary regulation. The problem of matching output to demand was faced by James Watt with his first steam engine. He solved it

with his flyball speed governor, a first proportional-action regulator known in the art. In its classical form, it consists of a flyball assembly, a slide valve and a servo.

The improvement of speed-responsive governing systems has resulted in new control devices which differ considerably from the above prototype. The difference becomes especially sensible with units rated for 300-500 MW and more, a feature characteristic of modern power systems. It is essential, therefore, before treating the topics concerned with primary regulation, to consider the characteristics of speed governors of modern turbines. These are as follows:

(a) Employment of intermediate amplifiers. All modern turbine governing systems may be considered as indirect-action systems which are fitted with supplementary amplifiers installed between the speeder motor and the slide valve of main servomotor. Early versions of the systems were equipped with hydraulic amplifiers and based on the "slide valve-servomotor" scheme. Modern systems utilize electrically operated amplifiers, or flapper-nozzle hydraulic amplifiers having a small dead zone. However, in such systems, the signal passes from the speeder motor to the slide valve of the main servomotor with a certain delay which tends to hinder the dynamic property of control;

(b) Increased number of main servomotors. An increase in the power output of a unit necessitates a more powerful control element, which cannot be, unfortunately, implemented as a single structure. As a result, many modern units are provided with several main servomotors. In the case of steam turbines, each of the main servomotors acts on its own group of valves, which are made open in a certain succession. In hydro turbines, the main servomotors are operated in parallel. Here the constructions are being developed which utilize an individual drive (servomotor) for each vane of the water gate. Under these circumstances, we can thus treat an idealized control scheme merely on the basis of the equivalent servomotor;

(c) A variety of constructions and functional capabilities for speed governors. With the advent of more compact and flexible means for amplification and transmission of signals in speed governors, and also new tasks concerned with an increase in the unit power output, power engineers try to expand the functions of turbine governing systems and give them new operational capabilities depending on the existing constructions of speed governors. Of course, it would be impossible to describe all speed governors available. Thus we shall deal only with certain speed governors, known in the Soviet Union, and with their future trends in accordance with two types of turbines: hydraulic and steam.

Hydroturbines. In the period of 1960-1965, hydraulic turbine governing systems were generally replaced with electrohydraulic

systems. An electrohydraulic turbine governing system is a system in which the signal proportional to the unit speed is produced and preamplified electrically, while hydraulic elements of the system are responsible for final amplification and use of that signal.

The fact that electric couplings were employed in hydroturbine governors resulted in rapid introduction of hydroelectric control schemes. A typical hydro unit had a small angular velocity and failed to speed up the flyball assembly, which therefore took power from an electric motor fed by a generator on the turbine shaft. Thus, the advent of adequate methods for the electric measurement of the speed (frequency) of the units and the amplification of the produced signals before applying them to the hydraulic section of the system allowed power engineers to utilize electrohydraulic governors for hydroturbines.

Further, a high level of automation associated with hydropower plants provides for the use of electrohydraulic governors with them. Indeed, control procedures for such plants are much more simpler than those for thermal power plants. On the other hand, hydropower plants often have a large number of units (20 and more) and are operated as regulating plants in a power system which are responsible for frequency control. Therefore, hydropower plants often utilize the operating mode known as a group control of units. In this mode, all the units of a plant are considered as a single group having a preset total power output or, most frequently, a preset total opening of the water gates (WGs).

In a group control system, a multi-loop servo responds to a control signal which is characteristic of the total value of the given variable, usually a water-gate-opening-acknowledgement signal. Under these circumstances, the individual signals relating to frequency deviation are present without affecting the system, since the gain concerned with a variation of the water gate position is high. Depending on the methods of control, different group control systems are available which utilize the corresponding governors.

Let us now consider the operation of a speed governor, type ЭГР-2М, manufactured by the Leningrad Metal Works. With the governor, it is possible to control a unit either individually, or in a group control mode utilizing four different schemes. The governor (Fig. 2.4) basically consists of a frequency deviation pickup *FP*, a signal summation-and-amplification element *SAE*, an electrohydraulic converter *EHC*, a driving slide valve *DV*, an auxiliary servomotor *AS*, a main slide valve *MV*, a water gate servomotor *WGS*, a turbine governing mechanism *TGM*, and feedback loop elements including a speed regulation changer *SRC* and a proportional-integral device *PID*.

The frequency deviation pickup *FP* measures the frequency of the voltage signal received, and produces a frequency deviation

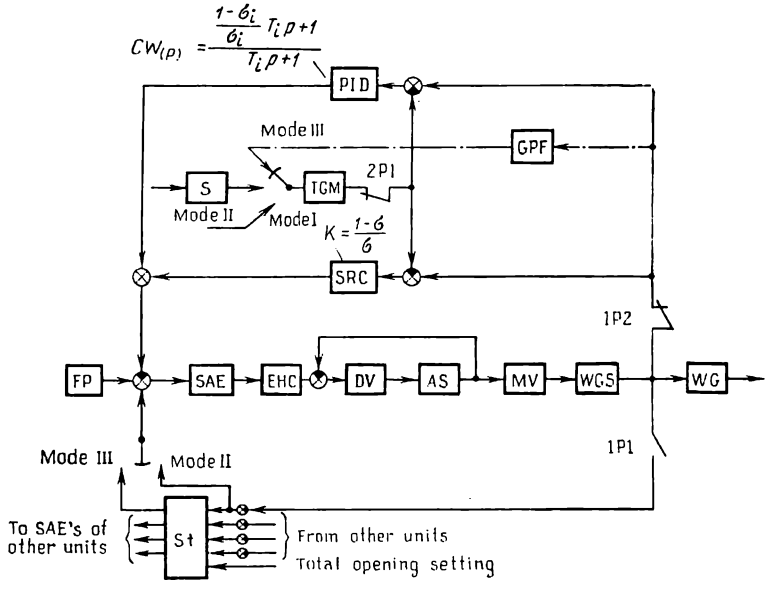


Fig. 2.4

signal. Note that the nominal value of frequency can also be controlled by varying the position of the corresponding elements. The signal summation-and-amplification element (*SAE*) (also known as a signal-acknowledging element) operates to sum up the signals applied to it, and to increase their power level. The electrohydraulic converter (*EHC*) (an actuator) converts the electric signals obtained from the SAE into mechanical movement of the corresponding parts of the turbine governing system, which performs the functions of a conventional hydraulic regulator.

There are the following operational features of the speed governor:

(1) Like most of electrohydraulic regulators, it has its main feedback established electrically and not mechanically;

(2) The point of connection of the turbine governing mechanism (*TGM*) also known as a power output changer (*POC*) or a speed changer (*SC*) is so selected that its signals pass to the output of the control system via two channels, proportional and differentiating.

These channels are formed from the elements of the feedback circuit, which is proportional-integral (like those in all hydroturbine governors). The circuit is described by the transfer function of the following form

$$W = K_{fb} W_{fb}(p) \qquad (2.17)$$

Thus we have

$$W_{fb}(p) = \left\{\frac{1-\sigma}{\sigma} + \frac{[(1-\sigma_i)/\sigma_i]\, T_i p}{T_i p + 1}\right\} \frac{1}{K_{fb}} \qquad (2.18)$$

where σ is the speed regulation of the unit in a steady-state condition, with $t = \infty$; σ_i is an extra "time-dependent" speed regulation having its greatest value at $t = 0$ and its zero value at $t = \infty$ ($\sigma \approx 5\%$, $\sigma_i = 20\text{-}30\%$), and T_i is the proportional-integral time.

A vanishing feedback is established in hydroturbine governors in order to resist a water hammer that occurs in the units. During small load fluctuations, it causes the appearance of the following factor in the transfer function

$$W_r(p) = 1 - Tp \qquad (2.19)$$

with the result that the stability of the closed system "turbine-speed governor" drastically impairs. Thus the need arises to reduce for some time the gain of the system and, consequently, increase speed regulation. However, it follows from the recent investigations that the above impairment takes place mainly in the case, where the unit is operated independent of the network. After the unit has been inserted into the network, there appear conditions in which the value of σ_i can be considerably reduced. In many governors, provision is made, therefore, for the employment of two values of σ_i, namely, an increased value with which the unit is operated at no-load, and a decreased value, which is selected automatically after the unit has been inserted into the network. In the governor under consideration, yet another approach to the situation is used: the point of connection of the *TGM* is chosen in such a manner that a vanishing feedback acts only on the signals from the *FP* and does not affect the signals produced by the *TGM* and the unit responds to the latter in a more rapid way.

The given speed governor provides the following control modes for each of the units:

I—individual control mode in which the *TGM* is operated manually in a direct fashion (via a special-purpose electric motor). In this case, contacts *1P1* are made open, and contacts *1P2*, closed. The proportional-integral feedback is established;

II—group control mode in which the *TGM* is operated via a synchro *S*, which is connected to the group control synchro operated manually. Contacts *1P1* are made closed, and contacts *1P2*, open. Direct feedback is established;

III—group control mode effected by virtue of a setter *St*. Direct feedback is established. The *TGM* is disconnected (with contacts *2P1* open) and coupled to a water gate position follower *GPF*. This provides for a continuous matching of the position of the *WG* and *TGM*; as a result, the initial loading of the unit is held constant during transfer from mode *III* to mode *II* or mode *I*.

There are several variants of mode *III*, which depend on the method by which the setter *St* produces its signals:

the setter signal is proportional to the required total opening of the water gates of plant units, no account being taken of the number of units being operated. In this case, disconnecting one of the units causes a variation of the settings on the other units (power swing);

the setter signal depends on the number of units being operated, and no power swing occurs during unit disconnection. In both cases, however, the setter produces its signals only in accordance with the required value of the total opening, no account being taken of the position of the water gates of the individual units. This may lead to uneven opening of the water gates, a condition requiring yet another variant of mode *III* below;

the setter signal is formed in accordance with the required total opening, with the number of the units being operated taken into account, but a new operation is performed by the setter during which the openings of the individual water gates are equalized.

The possibility of transfer from one variant of mode *III* to another results in a better quality of control; here, because of an increase in the number of equipments and circuits, their reliability is impaired. We can see, therefore, that proper selection of a given type of control depends on the operating conditions of the existing stations.

Steam turbines. In the 1950s-1960s, steam turbines of comparatively small output, connected with the main steam pipe of the station, were replaced with block-type powerful units utilizing supercritical steam parameters and fitted with intermediate superheaters. This led to a change in the characteristics of steam turbines treated as controlled objects. To improve the characteristics, some measures were taken; for example, turbine governing systems were provided with electric attachments.

Figure 2.5*a* shows a block diagram of a unit fitted with an intermediate superheater also known as reheater. The unit basically consists of a high-pressure section *HPS*, a medium-pressure section *MPS*, and a low-pressure section *LPS*, an intermediate superheater *IS* being installed between the *HPS* and *MPS*. The amount of the steam contained in the intermediate superheater is so high that aperiodic approximation of its dynamic characteristics requires that the time constant of the aperiodic element, *Tp*, be equal to 4-5 s.

With such a construction, steam turbines were subject to several important modifications, including the use of reheat stop or interceptor valves.

To gain an understanding of the purpose of interceptor valves, consider the case where a load drop occurs when the unit, for example, is disconnected from the network. In this case, steam admission

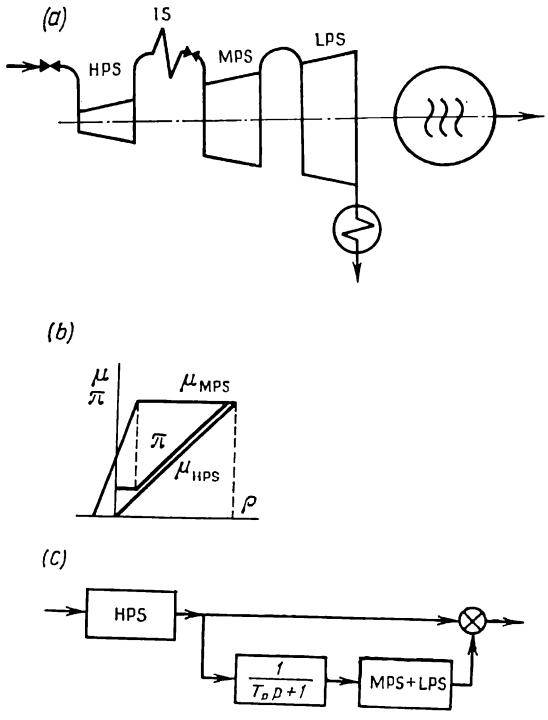


Fig. 2.5

to the turbine under control must be quickly interrupted. This resists the speed-up of the turbine above the nominal speed. If the latter is exceeded, the emergency control scheme operates and the turbine stop valves are closed. The emergency control schemes of modern steam turbines are designed to operate when the nominal speed is exceeded by 8-10% and steam admission must be interrupted in this case within 0.2-0.3 s.

Though it is possible to stop steam admission within the above time interval, the operation is efficient merely in relation to the high-pressure section (see Fig. 2.5*a*, *b*). As to the medium-pressure section, the torque developed therein tends to reduce with the intermediate superheater being emptied, i.e. a process takes place with time constant Tp. Of course, such a process is impermissible, and auxiliary interceptor valves are thus to be installed after the intermediate superheater to resist steam admission to the high- and low-pressure sections.

Throttle control of steam admission through reheat stop valves is economically inefficient. As a result, during system normal opera-

tion at all loads except very small ones (10-15%), these valves are always held fully open. Figure 2.5*b* shows an opening diagram for the valves. When determining the dynamic characteristics of a unit in normal operation (with small load fluctuations), one takes no account of the reheat stop valves and treats the turbine as a structure including two branches as follows: one branch having the high-pressure section located directly after the regulating valve, and another branch with the medium- and low-pressure sections, which is isolated from that valve by the reheater (Fig. 2.5*c*). With a standard allocation of power output among the turbine stages (about one-third of it on the *HPS* and the remainder on the *MPS* and *LPS*), the transfer function for a unit in the case of small load fluctuations is

$$W_a(p) = \frac{1}{3} + \frac{2}{3(T_p p + 1)} = \frac{(T_p/3)(p+1)}{T_p(p+1)} \qquad (2.20)$$

We see that (2.20) considerably differs from the expression dealing with the transfer function for turbines having no reheater. It follows from (2.20) that with rapid load fluctuations merely one-third of the power output of the unit is involved in primary regulation. This is equivalent to saying that there is an imaginary unit whose power output is one-third of the nominal rating of the given unit or whose speed regulation is three times that of the given unit.

To correct this situation leading to a drastical decrease in the pick-up property of the unit, a number of approaches may be utilized which generally reduce to a forced overopening (or overclosing) of the regulating elements of the unit during the initial stage of control. This should be done in proportion to a decrease in the unit response to a change in its load in order to compensate for the above increase in the initial frequency deviation (speed regulation of the unit). Among the recent practical applications there exists the only method as yet, called the initial correction of speed regulation (ICSR).

The signal η_{ICSR} applied to the turbine governing system in parallel with the speed deviation signal η_ω is

$$\eta_{ICSR} = k_{ICSR}(\rho - \pi) \qquad (2.21)$$

where k_{ICSR} is the gain and ρ and π are the relative values of the unit load and the reheater pressure, respectively.

It follows from Fig. 2.5*b* that $\pi = \rho$ in a steady-state condition. With a new value of ρ, this condition is disturbed and cannot be restored until a new value of π is reached. The resulting signal is further applied to the turbine valves. We can easily see that with $k_{ICSR} = 3$, the dynamic characteristic of the turbine with reheater and ICSR facility resembles, in the case of small load fluctuations, that of a turbine without reheater.

The ICSR principle was implemented first in the governing system of a 300-MW turbine at the Leningrad Metal Works.

Figure 2.6 shows a block diagram of the governing system of this turbine, including a conventional hydraulic system and an electric section thereof, known as an electric attachment *EA*. The system so obtained is similar to an electrohydraulic governor *EHG*, but a marked difference between them consists in the fact that the former has its hydraulic section performing main control functions, while the electric attachment is designed to provide for an increased pick-up property during small load fluctuations. It is convenient, therefore, to describe now the hydraulic section of the system shown in the upper portion of Fig. 2.6. The input to the hydraulic section is formed from three assemblies as follows: an electrohydraulic converter *EHC*, a turbine governing mechanism *TGM*, and a speed governor *SG*. Here by the *speed governor* is meant a structure comprising a flyball assembly (called sometimes a flyball governor *FG*) and a flapper-nozzle hydraulic amplifier *GA1*.

In the electrohydraulic converter *EHC*, at the output of an electromechanical converter *EMC* connected to an intermediate slide valve *ISV*, there is another hydraulic amplifier *GA2* identical with *GA1*. The hydraulic section also comprises an intermediate slide valve amplifier *SVA*, which relies on the hydraulic spring principle. The amplifiers *GA1* and *GA2* operate in conjunction with the *SVA* to amplify the signals; with such a construction, lever-type links between the assemblies are not needed and their functions are taken over by hydraulic lines ensuring a variable flow rate of the working fluid. This provides for a sufficiently sensitive and precise system not requiring electrical measurement of the rotational speed, a feature characteristic of recently developed governors.

Referring to Fig. 2.6, the signals from the *SVA* are applied to the final preamplification stage—intermediate slide valve *ISV*—and received by an intermediate slide valve servomotor *SVS*. After that, the signals are passed via the above hydraulic lines and input to slide valves *SV* and servomotors *S* of regulating valves *RV*. The turbine has seven *RV*s preceding the high-pressure section and two *RV*s preceding the medium-pressure section; as stated above, the *RV*s installed before the medium-pressure section are made fully open long in advance of the opening of the *RV*s preceding the high-pressure section and are not practically involved in primary regulation.

Let us now consider the electric section of the governing system, i.e. the electric attachment *EA* (see Fig. 2.6). It basically consists of a summing magnetic amplifier *SMA* designed to sum up the signals produced by the electric attachment *EA* and to transmit them to the electromechanical converter *EMC*. The *SMA* has supplementary inputs through which the signals from external data sources

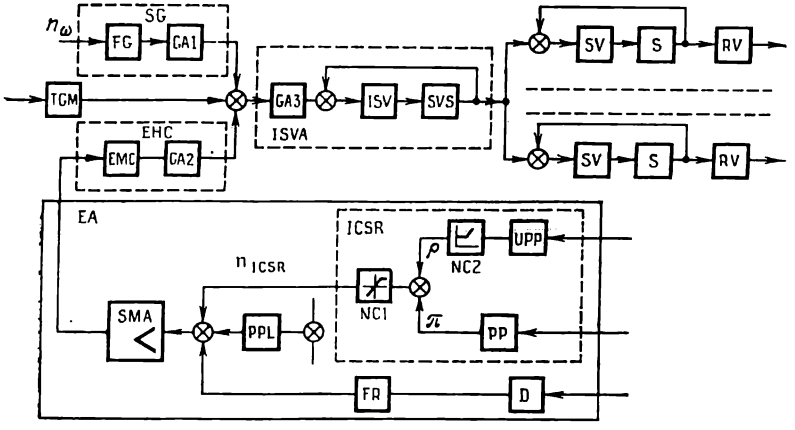


Fig. 2.6

(not shown in the figure) are input to the governing system. The remaining components of the electric attachment can be broken down into two groups. One group comprises a post-fault power limiter *PPL*, a differentiator *D*, and a frequency relay *FR*, which perform functions connected with emergency control and turbine protection. Another group includes components that constitute the ICSR channel.

It follows from the expression (2.21) that the main purpose of the ICSR channel is to select signals proportional to ρ and π. The electric attachment has for the purpose a unit power output pickup *UPP* and a pressure pickup *PP*. In addition, nonlinear signal conversion should be carried out in terms of power output. This arises from the fact that in the small load mode, with the *MPS* valves partially open, the value of π does not vary with a change in the mechanical power of the unit but is held approximately constant (see Fig. 2.5*b*). Thus the value of ρ should be varied nonlinearly and the corresponding signal is passed via a nonlinear converter *NC2* (see Fig. 2.6). The ICSR channel terminates in a nonlinear converter *NC1*, which serves to limit the signal during large load fluctuations.

The above electric attachment is among many electric automatic equipments that have been designed in recent years for governing systems of steam turbines. Such equipment proved to be effective since it provides for the solution of all problems connected with functional conversion and preamplification of the respective control signals on a more simpler and cheaper basis as compared to purely hydromechanical control devices. Another useful feature is good operational flexibility of electric control schemes, including their ability to easily accept modification work on the complete gover-

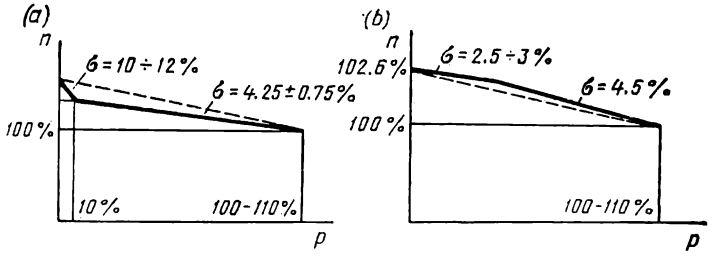


Fig. 2.7

nors, etc. As a result, many turbine manufacturers are introducing such schemes on a wide scale.

For example, modern practice of a number of companies in the United States, Western Europe and Japan is tending towards turbine governors in which all basic functions concerned with unit control are performed by the electric section of the governing system, while the required control signals are applied to the valves via an electrohydraulic converter. In some cases, several EHCs are used, each acting on its own valve, and the electric section is equipped with comparatively complex data processing means, including minicomputers.

With such schemes, enhanced functional capabilities of the governing system make it possible to perform some logic operations, for example, during startup and shutdown, and simplify the connections established between the governor and the human operator, and also between the governor and the secondary regulation system. It should be noted, however, that in this case the structure and specification of the main control loop are subject to minor modifications which do not affect considerably operating conditions. On the other hand, hydromechanical governing systems have greater reliability than electric governing systems. As a result, schemes are built which either have no electric section, or have certain electric components responsible merely for protection of the units from acceleration (as in the scheme developed by the Kirov Turbine Building Works in Kharkov).

Given below is a general description of the characteristics of primary regulation.

1. *Static characteristics* $n=f(P)$. Hydroturbines usually have linear static characteristics, while some other forms are found in the case of steam turbines. Figure 2.7*a* shows characteristics of the turbines manufactured by the Leningrad Metal Works with an increased speed regulation in the region of small loads, with the result that a better stability of control is provided for this difficult-to-regulate region. There are turbines (Fig. 2.7*b*) available from the Kharkov Turbine

Building Works, which have a decreased speed regulation in the region of small loads. This provides for a greater gain and, consequently, a higher closing-initiating signal at the moment when the turbine speed reaches its greater values after load drop.

This discussion deals with characteristics of the individual units. In the case of power systems, such characteristics are of a more complex nature. Here, a stepwise change in the generating capacity may be given by

$$K_s = \Delta P/\Delta f \qquad (2.22)$$

where K_s is the slope of the frequency-response curve for the system and ΔP and Δf are respectively changes in power output and frequency in relative units.

It is important to stress that the above case concerns the situation in which some units of the system operate at full load and cannot, therefore, respond to signals from the speed governor.

Under these circumstances, the resulting slope of the system frequency-response curve (or its reciprocal—the resulting speed regulation) mainly depends on the amount of the reserve capacity. Thus, the value of that slope shall be capable of adjustment in a wide range between 6 and 17.

2. *The governor dead band.* According to the recommendations adopted by the International Electrotechnical Commission, a standard level of the dead band for turbine speed governors is fixed at 0.06. The Maintenance Regulations for Electric Stations and Power Systems state that the standard value of the dead band shall not exceed 0.3% (0.15 Hz). However, actual values of this quantity depend on the constructional features and condition of the existing governors. In practice, there are cases where postemergency or system tests show that much more greater values are present. In this connection, we shall recognize that the instantaneous change in frequency, resulting from the relative oscillation of generator rotors, causes most of the governors to operate outside the dead band. As a result, considerable lower values of the dead band may be obtained during field tests.

3. *Statistical characteristics.* These are used to depict system frequency variation and may be treated in different ways. For example, the Maintenance Regulations for Electric Stations and Power Systems state that a maximum deviation of frequency from its present value shall not exceed 0.2 Hz provided that the mean frequency deviation for 10-min period is not more than 0.1 Hz. There is another characteristic of a similar type, i.e. the root-mean-square frequency deviation. In modern systems, it shall be within a range from 0.02 to 0.05 Hz.

The classification of time-dependent frequency variations as adopted by power engineers is as follows. There are per-second

variations whose period lasts for a few seconds. By centering the readings of per-second variations, one can obtain per-minute variations. It is feasible to classify the variations in this manner since, in particular, the variation in the opening of the valves of a steam turbine requires that the operating conditions of the boiler be changed accordingly; but it is clear that to perform the latter of the two actions takes minutes, and not seconds. In addition, with such a classification, it is possible to determine a fashion in which the system load tends to vary, thereby ensuring proper operation of secondary regulation facilities.

Secondary regulation. Control actions intended to vary the settings of the speeder motors are known as *secondary regulation*. The latter is slow and obeys a proportional-integral law to provide for higher accuracy of control. In Soviet practice, secondary regulation usually includes three levels: unit, station, and system.

The unit level is used to maintain a given power output, obtained from the individual units. With steam turbines in which primary regulation settings are varied in most cases through speed changers, the unit-level governors are often pulse-type devices. The speed of operation of the latter depends on the response time of the units, and also on the requirements devised by turbine builders, which must take into account fatigue stresses occurring in turbine components. Therefore, the rate of change in load on turbines should not exceed, under normal conditions, 1-2% of the nominal power output of a unit referred to a per-minute time interval.

Important to unit-level governors are devices designed to limit power output from a unit in terms of two limits, upper and lower.

The station level deals with the control action applied to either the unit-level power output regulators or directly to the primary regulating devices, for example, synchrotransmitters of hydroturbines.

The systems level deals with the control action, which takes into account the requirements imposed on the operating conditions of a power system, as a whole. In the case of a power system with free tie-line power flows, the system control provides for a limitation of power flowing through both in-systems and intersystems tie lines.

There are many control schemes of the type just described. Let us now consider one of such schemes used at the Central Control Board of the USSR UPG. This scheme (Fig. 2.8) basically consists of a telecontrol receiver TR, power output limiters PL, a switching panel SP, and regulating telecontrol transmitters RT.

The telecontrol receivers receive data on the load level available to the transmission lines under control, P_{li}. If the load exceeds the limit value of power exchange, P_{si}, the operator has chosen by means of a setter S_p, then the resulting difference is trans-

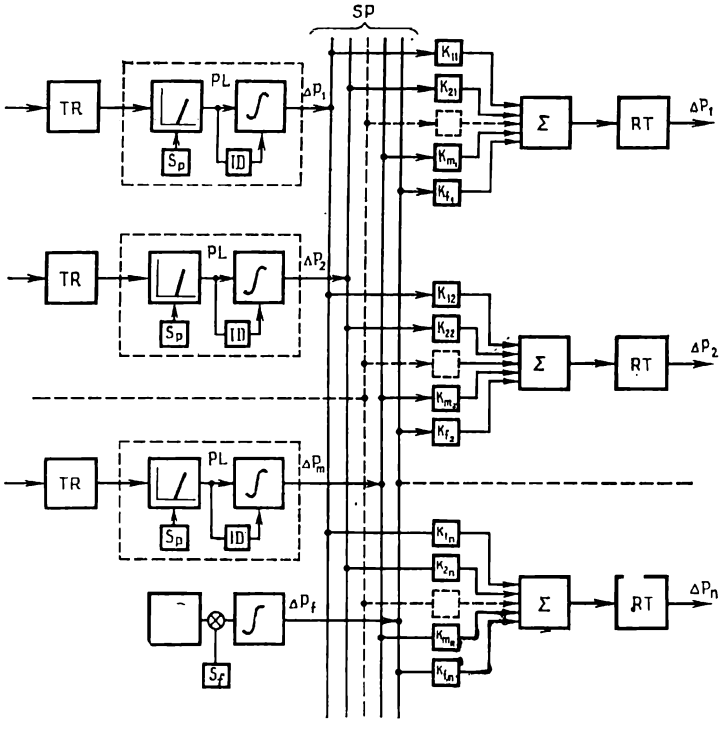


Fig. 2.8

mitted to the power output limiters, which comprise electromechanical integrators belonging to the type described in Chapter 5.

In some cases, one has to limit not the power flowing through one line, but the total power on several intersystems tie lines, referred to a critical section. So, a power output limiter produces an output signal given by

$$\Delta P_t \leqslant \int \sum_i (P_{it} - P_{si}) \tag{2.23}$$

Here, one must allocate the produced signal among the stations that are involved in control of the given power exchange, and remove the signal in the case where the value of the power flow drops below its lower limit.

The first task is implemented by using the participation coefficients, which determine that portion of the total value of ΔP which should be picked up by a given station. The participation coefficients are computed in advance and selected on the switching panel

SP by means of setters K_{ij}. If the first subscript in the coefficient K stands for the power flow to be limited, and the second one, for the regulating station, then the total signal received by the station j is given by

$$\Delta P_j = \sum_i K_{ij} \Delta P_i \tag{2.24}$$

The second task is dealt with as follows. If P_l becomes lower than P_s during the control process, then an interlock facility ID actuates the power output limiters, with the result that their integrators are reset.

The described system can also be used to effect a centralized frequency control. In this case, a pickup is used, whose function is analogous to that of a power output limiter PL, to measure the frequency deviation Δf from its nominal value S_f.

If the pickup signal counteracts the effect of the power output limiter signal, then an interlock device (not shown in the figure) actuates the pickup to remove its signal until the above counteraction ceases.

The operator can use a telecontrol wattmeter of the given line to monitor system operation and vary the limiting settings. In addition, the operator should be able to vary in a direct way, by means of the corresponding setter, the power output from a given station, thereby effecting remote control over it.

With the power output limiters replaced by proportional integral regulators, the system can be operated in the controllable tie-line power flow mode; at present, modification work on the system concerns the replacement of its analog devices with digital ones.

There exists the opinion that the power limitation function is responsible for the suppression of two-minute load fluctuations, and the regulation function, of ten-minute fluctuations of the load. It should be noted, however, that the amplitude of the power flow fluctuations (the so-called unplanned changes) is small and usually amounts to not more than 3% of the scheduled value; this means that no optimization procedure is required in this case. Greater load fluctuations, connected with such unpredictable events as weather change or a sudden loss of a particular piece of equipment, can be dealt with by tertiary regulation procedures.

Tertiary regulation. This is performed by load schedulers, which provide the station-level section of the ALFC system with data on the load pattern of a given object. It is evident that a load scheduler is a nonlinear device, which handles data as a function of a single variable, i.e. time. Among load schedulers are photo-sensitive devices for reading function plots from a piece of plotting paper and potentiometers with taps being switched over according to a preset program to provide for the required load values to appropriate scale.

Modern practice is tending towards autooperators with semipermanent storage, which replace load schedulers of the above types. In the former, data is input by means of punch cards, while a function graph is scanned by pulses produced by a quartz clock.

Further, tertiary regulation provides for a real-time correction of the operating conditions in accordance with the control signals available from the control engineer. To this end, many systems utilize analog computers, type "EKRAN" and "ANRAN" and also digital computers as consulting devices for the control engineer.

Given below is the description of the Soviet-made real-time correction system, which handles system operating conditions in conjunction with a computer and data input/output devices.

Figure 2.9 shows a structure and operating modes of the system. Proper operating conditions of a power system are maintained on the basis of scheduled load flows determined by the system service personnel from consumer demand forecasts for the power system and from the operational planning program for the operating conditions of an interconnected power system. To schedule load flows, use is made of data base available in magnetic tape units and also fresh data obtained from the operating conditions personnel. The calculations are made by using the method of incremental costs, transmission losses being taken into account. The data so obtained is transmitted to an alphanumeric printer which produces scheduled load patterns used by the control engineer.

At the same time, the results of planned calculations are recorded on magnetic tape so that data base for real-time correction is provided. The data base comprises all data relating to the planned period, including a most important information on generating mix.

Assume that some changes occur in the course of realization of planned operating conditions, which may be as follows: the load on buses deviates from its expected value, for example, due to weather fluctuations; the preset generating mix changes when certain generators, lines or transformers are lost in the time of emergency; the preset limits of power output change due to the fact, that the state of equipment is impaired or due to other analogous causes. In the case of any of these changes, the control engineer's duty is to make decision on a correction of the load pattern and send the corresponding message to the control personnel. Note that the corrective decisions, as in the case of planning, must provide, in any existing situation, for optimum system operating conditions in terms of economy and reliability.

In early stages of control development, control engineers used for the purpose very simple means such as tables, slide rules, etc. With the advent of computers and associated communication facilities (even the simplest ones, such as a typewriter on the contro

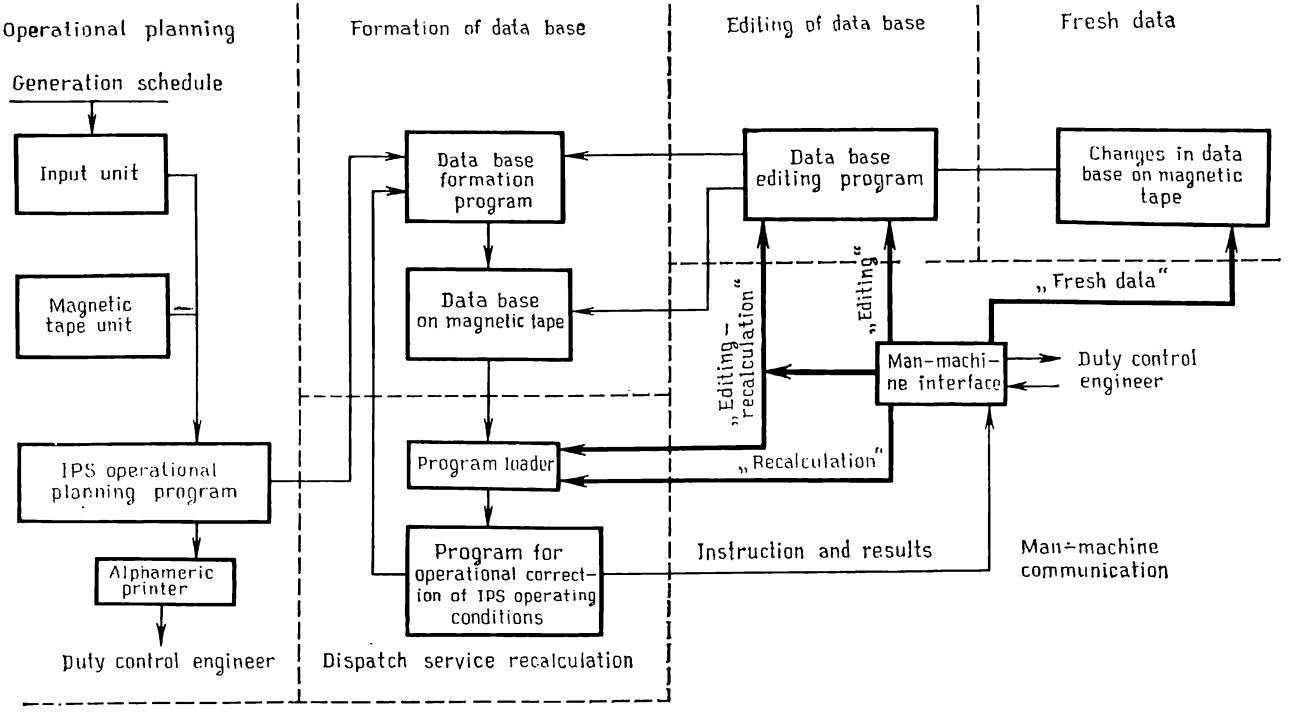

Operational planning
Formation of data base
Editing of data base
Fresh data
Generation schedule
Input unit
Magnetic tape unit
IPS operational planning program
Alphameric printer
Duty control engineer
Data base formation program
Data base on magnetic tape
Program loader
Program for operational correction of IPS operating conditions
Dispatch service recalculation
Data base editing program
Changes in data base on magnetic tape
„Editing – recalculation"
„Editing"
„Fresh data"
Man-machine interface
Duty control engineer
„Recalculation"
Instruction and results
Man-machine communication

Fig. 2.9

desk), the control engineer is able to perform the necessary corrections in a more simple and accurate way.

Referring to Fig. 2.9, to deal with one of the above situations, the control engineer commands the computer to operate in the recalculation mode, when the problem is to be solved without changing the generating mix, or in the recalculation-and-editing mode when the problem solution requires a variation of the generating mix.

The request message from the control engineer is passed via the man-machine interface system which communicates it to the data base editor program or directly to the program loader designed for real-time correction of the operating conditions of an interconnected power system. This program is conversational. It can perform recalculation immediately or initiate a request for transmission of extra data from the control engineer, and then, perform new computations. The request for extra data is labeled in the figure by the word "Instruction".

It is evident that the data so obtained can be transmitted, when checked by the control engineer, to the station dispatching offices in any convenient way, for example, automatically.

2.6. Control of Normal Operation of Power System with Controllable Tie-line Power Flows

As stated above, the controllable exchange of power in power systems is generally employed to fulfil the contractual agreements concluded by the various power undertakings. In this mode of operation, the functions of primary regulation and station-level secondary regulation are the same as in the case of free tie-line power flows, but the system-level secondary regulation has certain different features discussed below.

System structure and principle of its operation. With an interconnection of the simplest type, consisting of merely two parts, the power flowing through a tie line that connects them is easy to adjust by using only one, and any one, of the parts.

There is another situation, in exact opposition to that just described, in a complex interconnection that includes more than two parts. If all the parts are united with one another through tie lines, one fails to maintain interchange flow on schedule by adjusting the power flowing through one of the tie lines with the above mentioned method. This is due to the fact that any change in the generation of one part immediately results in a simultaneous variation of the power flows through all the tie lines.

The only way out is *to effect control simultaneously over all parts of an interconnection* by maintaining the algebraic sum of the power flows in and out of the parts (area net interchange). This method is used in the area regulation principle.

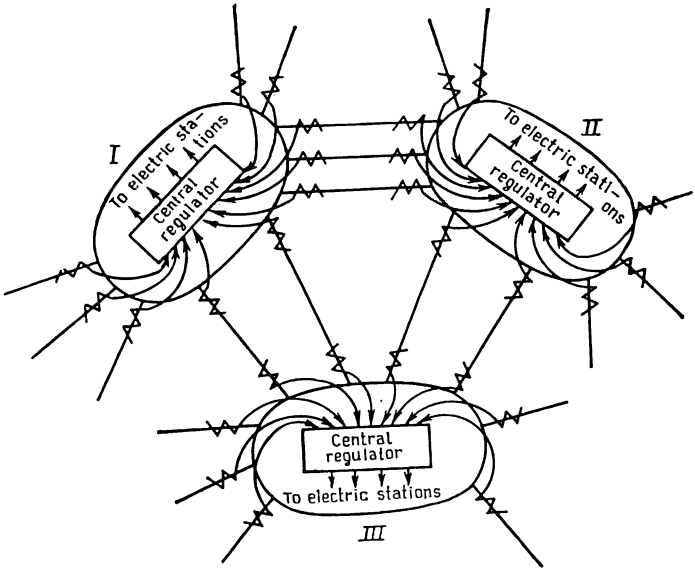


Fig. 2.10

Figure 2.10 shows a three-area portion of an interconnection. There are transmission lines to link the areas together and connect them to other areas within the interconnection. According to the principle of the system operation, each area must have its own central regulator, which is designed to receive data on all power flows out of that area. The regulator operates to compute the area net interchange, determine its deviation from the preset value and allocate the deviation among all regulating stations or units of the area. To provide for a condition under which the areas can adjust their generations independent of one another, use is made of the frequency-bias-tie-line control principle.

Frequency-bias-tie-line control. Also known as *network flow control*, it relies on the principle that an error signal produced by the area regulator (area requirement) is given by

$$\varepsilon = \Delta P + K_f \Delta f \tag{2.25}$$

where ΔP is the algebraic sum of power flows in and out of the area, K_f is the frequency-signal gain, and Δf is the system frequency deviation. With K_f chosen according to the expression

$$K_f = \frac{P_{nom}}{f_{nom}} \frac{100\%}{\sigma} \tag{2.26}$$

where P_{nom} is the nominal generation of the area, f_{nom} is the nominal frequency, and σ is the speed regulation, %, the area is allowed to absorb any load change that occurred within its boundaries.

This may be easily illustrated for a three-area interconnection shown in Fig. 2.10, the areas being labelled respectively as *I*, *II*, *III*. Let us assume that nominal generations of the areas are $P_{nom1} = P_{nom2} = 1\,000$ MW, $P_{nom3} = 10\,000$ MW, nominal frequency $f_{nom} = 50$ Hz, and speed regulation $\sigma = 6.66\%$ ($K_g = 15$). According to (2.26), the frequency-signal gains are

$$K_{f1} = K_{f2} = 300 \text{ MW/Hz and } K_{f3} = 3\,000 \text{ MW/Hz}$$

Further, assume that under certain load conditions, with $f = f_{nom}$, there exists an exact balance between area generation and load, and the following equalities are satisfied

$$P_{r1} = P_{nom1} = 1\,000 \text{ MW}, \quad \Delta P_1 = 0$$
$$P_{r2} = P_{nom2} = 1\,000 \text{ MW}; \quad \Delta P_2 = 0$$
$$P_{r3} = P_{nom3} = 10\,000 \text{ MW}; \quad \Delta P_3 = 0$$

Let the above conditions change in a way that the load on area *I* experiences an increase of 180 MW. This results in a decrease in the interconnection frequency by the following value

$$\Delta f = 50 \frac{180}{1\,000 + 1\,000 + 10\,000} 0.0666 = 0.05 \text{ Hz}$$

Under these circumstances, the signal responsible for the total extra load will be part of the signal produced by the secondary regulation facility of that area in which this load change occurred, and the total extra load will be absorbed by the units of the area, provided they have the appropriate reserve capacity. Since the secondary regulation law always includes the integral component, the system frequency will assume its nominal value during the regulation process and generations in the remaining areas will be maintained at the previous level.

The algorithm of the above operational steps depends on the construction and principle of operation of the regulator. At present in the United States, wide use is made of *base point and participation control principle*. Here, the base point P_b is a point on the load schedule plot of the station or a unit in the vicinity of which power fluctuations occur during regulation. As previously, by the participation coefficients ρ are meant the coefficients representing those portions of the total deviation of the controlled quantity from the preset value which are shared by the respective stations or units.

Figure 2.11 shows a block diagram of the described governing system, which comprises two control channels: *I* dealing with power exchange, and *II*, with total area generation.

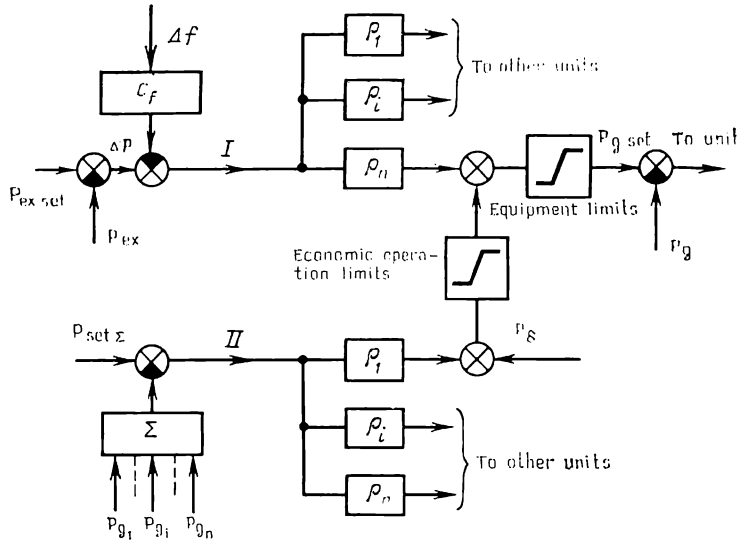


Fig. 2.11

The channel *I* operates to sum up the current values of the power flows of the area, P_{ex}, which gives the algebraic sum of the flows, to determine the deviation of that sum ΔP from the setting $P_{ex\ set}$, and to allocate the deviation among the stations or units concerned. In addition to ΔP, the signal δ produced by the channel includes the frequency deviation Δf multiplied by the K_f. Thus frequency-bias-tie-line control can be effected. The channel *II* operates to sum up the current values of the loads on generators, P_g, and compare the sum so obtained with the setting $P_{set\Sigma}$. The computed deviation ΔL is reallocated in proportion to the participation coefficients ρ of the stations or units and is added together, either at the station or unit levels, with the value of base load P_δ. After that, the channels *I* and *II* are operated jointly and their total signal is applied to the secondary regulation system of the controlled object, i.e. its power output controller generation at the object is adjusted to reach the level P_δ, and two corrections are introduced: one taking into account the value of ΔP and the other compensating for a change in system generation.

The described secondary regulation system operates in intimate cooperation with the tertiary regulation system effecting the economical distribution of load. The both are related to each other by virtue of the values P_δ and ρ, which are computed during tertiary regulation, the respective signals being delivered to the secondary regulation system in a substantially automatic way.

The existing methods of direct digital control make it possible to join together automatic tie-line power and frequency control systems, and economic dispatch facilities, with the result that a united generation control system is obtained which is able to perform all necessary operations on one and the same equipment. Given below is a brief description of such a system.

Digital generation control system (determination of design parameters). It is essential to stress that typical methods and algorithms devised for control of system generation in the case of controllable power flows are those which rely on the load-frequency control (LFC) and economic dispatch (ED) principles.

The generators that are subject to the above control actions can be controlled either automatically from the control room, or manually in accordance with the control signals sent by the control engineer.

For the generators of the first group, the LFC control actions are performed every two seconds, and the ED control actions, every three minutes. Note that there are similar systems in which the said intervals occupy 10-15 s, and 5-10 min, respectively. As to the generators of the second group, the ED control actions are carried out every 20 minutes, and no LFC control is effected at all.

In the case of economic dispatch, use is made of a conventional algorithm, which utilizes the principle that the incremental costs are subject to equality; in particular, use is made of the incremental costs referred to the units. Transmission losses P_L in a power system are given by

$$P_L = P_{cr}\,(\mathbf{B}P)$$

where P_{cr} is the row vector representing the current unit generations, **B** is the coefficient matrix, and P is the column vector representing the unit generations.

The coefficients **B** in the transmission loss formula depend on the variables and configuration of the network and are determined by using a transformation method. In Soviet practice, use is made of allocation coefficients k_l corresponding to the coefficients **B**, which give the sensitivity matrix α. Thus we obtain approximate relations depicting transmission losses. However, these relations are connected with the generations at the units and are linearized, thereby providing for the use of very simple optimization methods, for example, the gradient optimization.

In principle, one can compute the **B** or α matrices separately for each of the present operating conditions. This results, however, in cumbersome computations. A convenient way out is to prepare in advance two or more sets of such matrices, which enable one to handle the different operating conditions of a power system.

The LFC system can implement three types of control as follows: isochronous frequency control; isochronous tie-line power control; and frequency-bias-tie-line control.

The LFC system is assumed to be responsive to the sense of the deviation of the controlled quantity from its preset value, rather than the deviation proper. Since the controlled quantity may fluctuate with a period less that the regulation time, the LFC signal δ' is smoothed out according to the following formula in order to remove an excessive regulating burden from the turbine governing system

$$\delta_{i+1} = M\delta_i + N\delta' \tag{2.27}$$

where δ_{i+1} and δ_i are the smoothed-out values of the current and previous LFC signals, N is a coefficient of proportionality chosen by the control engineer and usually equal to 0.3, $M = 1 - N$; and δ' is the non-smoothed-out current value of the LFC signal.

Depending on the magnitude of δ, we can use the following control modes, which pursue the differing aims and use the differing methods of generating control signals applied to the units:

$|\delta| < x$ (with x usually equal to 5 MW)—the dead band mode devised to ensure economic reallocation of the load within the area; and

$|\delta| > y$—the emergency assistance mode intended to correct the signal δ as quickly as possible, no account is taken of economy in this case.

To produce control signals U_s applied to the units, the following operational steps are to be performed.

The Dead Band Mode

(1) Determine the difference between the total load on a power system (area) at the moment of application of the current LFC signal and the amount of the load available at the moment when the last ED signal is applied

$$\Delta L = L_{\mathrm{LFC}} - L_{\mathrm{ED}} \tag{2.28}$$

(2) Compute the vector representing the desirable generations at the units by

$$\overline{P}_{\mathrm{LFC}\,d} = \overline{\rho}\Delta L + \overline{P}_{\mathrm{ED}} \tag{2.29}$$

where $\overline{\rho}$ is the vector representing the participation coefficients of the units that absorb ΔL, which vector being determined on application of the last ED signal, and $\overline{P}_{\mathrm{ED}}$ is the vector respresenting the power output settings on the units on application of the last ED signal.

(3) Compare the value of $\overline{P}_{\mathrm{LFC}\,d}$ with the values of the vectors representing either minimum or maximum generations at the units. When either of the two limits deviates from the preset level, the

respective participation coefficient is reduced to zero, while the remaining participation coefficients are recalculated in a way that their sum reaches unity again.

(4) Compute the desired changes in the generations at the units

$$\Delta \overline{P} = \overline{P}_{\text{LFC } d} - P_{cr} \tag{2.30}$$

where P_{cr} is the current setting of the generation at the unit.

(5) Compute the control signals applied to the units by

$$U_s = W \Delta \overline{P} \tag{2.31}$$

where W is the gain obtained during economic reallocation of the unit generation.

Normal Control Mode

(1) Compute control signals applied to the units

$$U_s = G \delta \overline{\rho} + W \Delta \overline{P} \tag{2.32}$$

where G is the gain chosen by the control engineer and usually equal to 0.9, and $W \Delta \overline{P}$ is the quantity found from (2.32).

(2) Compare the future generations at the units with their limit values and introduce corrections, if necessary.

The Emergency Assistance Mode

(1) Determine control signals applied to the units by

$$U_s = G_{ea} (\overline{P}_m - \overline{P}_{cr}) \tag{2.33}$$

where G_{ea} is the gain for the emergency assistance mode usually equal to unity and $\overline{P}_m$ is the upper or lower limit of generation at the unit, which depends on the sign of δ.

The analysis of the algorithm obtained for digital load-frequency control shows that it corresponds fully to the described method of control utilizing base point and participation principle in the case of normal control mode. The dead band mode, however, allows for a deviation of the controlled variables from their preset values, with the result that an excess regulating burden is removed from the control devices of the units. In the emergency assistance mode, the control signal of a maximum permissible level is applied to the units and the regulating capability of the area is employed to the fullest extent.

Note that the feature just described can be applied to the normal control mode by drastically increasing the gain G with $\delta > y$. Such a mode is encountered in systems with controllable power flows and is known as *rapid control mode.*

The control signals U_s produced by regulating devices, in particular, digital computers, may be expressed in terms of megawatts. They must actuate the speed changers of the units so as to change their positions. This can be achieved by many different methods among which is a most commonly used method employing "raise" or "lower" pulse commands to increase or decrease generation, whose length is proportional to U_s. These pulse commands are transmitted via carrier channels or data communication channels and received by the relays that actuate the contactless switches in the circuits of the speed changers of the units. The regulating digital computer receives, in turn, the current values of the unit generations and also their upper and lower limit values.

As stated above, modern power systems are equipped with installations in which one digital computer can effect control over tens of units at distant electric stations. The serviceability checks for such systems employ different methods. For example, the operational steps of one of such methods are as follows: a periodic check to determine whether the total amount of control commands to change the generation at the given unit corresponds, within a certain time interval, to the actual change in the unit power output occurred within the same time interval and a check to determine the power system response to the LFC signals.

2.7. Voltage Control in Networks of Interconnected Power Systems

At the modern stage of integration of electric power systems, electric energy is transported and distributed by virtue of networks of complex configuration, which utilize a wide range of voltage ratings (0.4 to 750 kV a.c. and up to 1 200 kV a.c.) in future network configurations, and ±750 kV d.c.

The networks throughout many countries continue to grow and expand. For different voltage ratings, the networks belonging to the USSR Ministry of Power Industry (Minenergo) may be characterized by the following parameters:

Nominal voltage, kV	6-35	110	220	330	500-750
Network relative length, %	85	12	3.5	0.9	1.0

To complete the formation of interconnected power systems and provide for further development of the United Power Grid, it is necessary to vary the configuration and length of networks. Modern transmission lines rated for 330-750 kV provide a basis for a system-forming network and are used as intersystem tie lines; it is, however, certain that a.c. transmission lines working at 1 200 kV and 1 500-kV d.c. transmission lines will be required to handle large tie-line power flows in the near future.

The data below illustrate how total energy loss depends on the network voltage rating:

Voltage rating, kV	6-35	110	230	330	500-750
Total energy loss, %	35	38	17	6	4

It is clearly seen that the optimization of voltage control for networks working at 110 and 6-35 kV can give a maximum economy due to a decrease in total energy loss.

Voltage control is effected by means of regulating devices that provide for a controllable generation, reception and reallocation of reactive power. The controllable generation and reception of reactive power is attained by means of generators and synchronous compensators. Condenser banks are used to provide for the controllable generation of reactive power. In addition to generators and synchronous compensators, use is made of reactors in the case of the controllable reactive power reception. The controllable reallocation of reactive power is carried out by means of supply transformers equipped with the additional feature of automatic on-load tap changing (OLTC), booster transformers, and line regulators.

In most cases, the settings of the regulating exciters of generators are chosen in such a manner that steady-state and transient stabilities are ensured. In addition, account is taken of a dependence of the available reactive power of generators on their real load: the former decreases as the latter increases.

The proper place of installation and operating conditions of reactors are determined from the constraints on short-circuit currents and the condition of an increased transient stability of a power system. Thus the optimization of voltage control may be basically carried out through the use of controllable transformers and compensating devices (CDs) such as synchronous compensators and condenser banks.

As to the optimization criteria relating to voltage parameters, electric networks can be broken down into two groups as follows: subtransmission and distribution. The subtransmission networks include electric networks responsible for the transport of power and do not directly connect the consumers. The distribution networks are electric networks which connect (or may connect) the consumers.

Voltage optimization in subtransmission networks is carried out on the basis of the criterion of a minimum of total transmission losses. In distribution networks, however, optimum operating conditions must provide for the desirable quality of voltage across the consumer buses with minimum transmission losses.

This approach is meaningful only in the case when for the different operating conditions there exists a positive balance of reactive power at all buses and when subtransmission networks are coupled to distribution ones via the OLTC transformers with adequate adjust-

ment ratings. In most cases, unfortunately, certain load buses and sometimes certain areas of networks are deficient in terms of reactive power whereas the transformers that couple subtransmission and distribution networks are not equipped with the OLTC facility or the latter has an insufficient adjustment rating. Thus it is practically impossible to separately handle the voltage of subtransmission and distribution networks by using the two differing optimization criteria.

The solution of the voltage optimization problem to subtransmission networks is possible when account is taken of the voltage quality requirements to be met by distribution networks. To this end, the magnitudes of the nodal voltages of subtransmission and distribution networks are maintained at different levels as well as the characteristics of the existing regulating devices are normally constrained by the appropriate inequations.

At present, the problem of optimization of voltage profiles existing on electric networks is solved by planning the required voltage levels and maintaining them at the previously selected reference points. The latter coincide with those nodes of an electric network whose voltages are characteristic of the voltage quality in the whole area (part) of subtransmission and distribution networks.

It is good practice to select the optimum voltage levels at the reference buses by solving a combined problem of optimization of network electric parameters. There are two approaches to the problem as follows.

One approach relies on the principle that the operating conditions are optimized separately in terms of real power and voltage-reactive power. During the first operational step, one must solve the problem of optimum allocation of real power among the stations of a power system so that fuel rate is held at a minimum. Under these circumstances, to obtain the desirable quality of voltage requires that the limit ranges of variation of the voltages at the reference nodes be specified. The second operational step concerns the problem of optimization of the operating conditions in terms of voltage and reactive power, while taking into account a preset allocation of the real power flows. The deviations from the reference voltage that exceed the preset (limit) magnitudes are dealt with by using the penalty terms in the objective function being found during the optimization procedure.

With these techniques, it is possible to obtain rather good results in a simple way, while keeping the required computer time at a minimum.

There is a modification of the approach above in which the required magnitudes of voltage and reactive power are obtained during control of the operating conditions by means of an automated dispatch control system (ADCS). Here the deviations of the dependent and

independent variables from the preset optimum values are handled. This allows one to treat the parameters of the regulating devices as independent variables, and the network electric parameters as dependent variables. During direct control, one must seek to find the minimum of the sum of the squares of the deviation of the reference voltage from the preset optimum values. The optimum control involves finding the minimum of the total network losses when the deviations of the parameters of the regulating devices and also reference voltage deviations do not exceed the preset values. It is assumed that the deviations of the parameters of regulating devices are related linearly to voltage deviations. This linear relationship is determined by the corresponding elements of sensitivity matrices.

The modified method includes two operational steps as follows:

determination of sensitivity matrices by using the given scheme parameters and operating conditions;

determination of the desirable deviations from the parameters (settings) of regulating devices, which tend to minimize the sum of the squares of voltage deviations during direct control, or to minimize the total network losses during optimum control.

The calculation results obtained from the first operational step show that in a power system having no transformers with quadrature regulation facility no account may be taken of those terms in the objective function which depend on the transmission line real power flows. In this case, more simpler formulas can be used from which the elements of sensitivity matrices are determined. If load patterns for all nodes of a network have geometrical similarity, then the voltage-dependent elements of a matrix depend merely a little on the operating conditions and may be assumed to be constant when the initial load changes by 5-7%. This allows one to compute the sensitivity matrices in advance by using data on the planned operating conditions. As a result, the computers that are part of the operational control loop of the ADCS system may have a considerably lower speed of operation.

To design the algorithm of the second operational step, which deals with the determination of corrections for the settings of the regulating devices, use is made of a method of the conjugate gradients. Using the calculation results obtained, we may conclude that modern medium sized computers can implement operational control of the voltage of comparatively complex networks.

The other approach to the voltage optimization problem is an approach in which the operating conditions are optimized simultaneously in terms of real and reactive power flows and voltage levels at the reference nodes.

In this connection let us consider distribution networks that feature a sufficiently high repeatability of operating conditions (except those existing in the time of emergency). Here, for automatic volt-

age control, use is often made of a regression analysis method to establish relationships between the parameters characteristic of the operating conditions under consideration. These relationship-allow one to automate the voltage control procedure in such a man ner that neither computers nor a sophisticated system for collection and transmission of telemetered data is needed. However, the method requires that periodical measurements be carried out and the measurement results be handled in order to obtain the numerical values of the regression coefficients. Also note that any change in the network configuration results in the general case in a variation of the numerical values of the regression coefficients. The disadvantages above restrict the use of the method to those distribution network areas, which are responsible for the supply of power to the consumers of a permanent mix and which have their network configuration unalterable.

The growth and expansion of the ADCSs capabilities makes it possible to implement on a wide scale operational control of the settings and operating modes of all local regulating devices, thereby providing for the most profitable technico-economic characteristics of power system operation. Thus the optimum solution to the voltage control problem is achieved in the case where all regulating devices are equipped with local regulators whose settings fit with the most frequently encountered operating conditions of the distribution network coupled with the power system. Under these circumstances, the digital computers of an automated dispatch control system belonging to the upper control level work out on a centralized basis the correction signals influencing the settings and operating modes of all local controllers.

The proper operation of an automated dispatch control system does require that modern means of data processing gathering, transmission, recording and display be employed. The entirely new technical means necessitate the development of new approaches to the problem of control of voltage of electrical networks. True, it is necessary to equip electrical networks with adequate regulating and compensating devices. But there is another urgent problem: such devices must be used most effectively both at the stages of automated control, and also in the further stages of automatic control.

2.8. Power System Management and Control in the Soviet Union and Its Future Trends

Major trends in the development of the Soviet power industry. The main task involved in developing the power industry is the construction of the USSR United Power Grid which will cover, when completed, the consumers' loads throughout the country and transmit power to interconnections abroad.

At present, the Soviet Union has 93 power systems. 85 power systems operate in parallel, and are part of 11 interconnected power systems.

Energy is exported from the Lvov, Moldavian, Byelorussian and Leningrad power systems. The Lvov power system is operating in parallel with MIR interconnected power system belonging to the CMEA countries. The Moldavian power system supplies a separate area in the People's Republic of Bulgaria via the Vulkaneshty-Dobrudzha transmission line.

Between 1977 and 1980, the parallel operation of the USSR United Power Grid and MIR system was to commence by using a 750-kV interstate transmission line.

At the time of this writing, the USSR Ministry of Power Industry constructed powerful Sayano-Shushenskaya and Ust-Ilimsk hydropower plants, the state district power plant in Zaporozhye, and the Novovoronezh and Kursk atomic power plants; the essential national economic complexes—automobile plants in Togliatti and Naberezhnye Chelny and the Kamsk petrochemical integrated works; and took part in the construction of 136 power installations in 27 countries throughout the world.

There are reasons to suggest that by 1990, in accordance with the programs available, the USSR United Power Grid will be linked together with some power systems in the Western Europe through 750-1 150-kV a.c. transmission lines, or 1 500-kV d.c. transmission lines.

The ENERGIYA branchwise management control system. To successfully complete the formation of interconnected power systems, and thereby create the USSR United Power Grid requires that construction and commissioning of electric stations and networks working at different voltages be carried out on a more rapid basis. In this connection, further improvement of power system management and control is also necessary, and one of the most important problems concerned is the development of the ENERGIYA branchwise management control system (BMCS).

The ENERGIYA system is a united complex of mathematical, economic and administrative methods, which are based on modern computational, managerial and data handling means, and are capable of exercising most economical control over the power industry constituting a branch of the country's national economy as a whole.

The conceptual framework of the ENERGIYA system relies on the economic and methodological, systems analysis, and organizational and technical principles.

The economic and methodological principles involve constructing a joint economic and organizational model that represents the power industry in the form of a controllable object and determines the relationships and information-flow paths between the operational

functions and the control tasks in terms of the objectives, criteria and limitations defined. The following appear to be the generally accepted methods of implementing the above principles:

assigning the priority levels to the particular control tasks and defining the order of their development and introduction;

matching the industrial structure to the requirements and capabilities of scientific and technological progress, and also of the superiors and subordinates of the existing management control systems;

determining, on an explicit basis, the periodicity in the performance of all task ensuring a continuity of the steps of management control process.

The systems analysis principles include the following:

rationalizing the flows of working papers to minimize the number of documentation forms, keep paper control routes as short as possible and exclude duplicate routes;

inputting into computers the flows of working papers passing through the routes between management control centres and utilities, thereby providing for storage and regular updating statistical data and data available from standards and regulations;

determining an optimum time schedule which all entities of the BMCS are to follow in the performance of their duties so as to evenly distribute data processing and storage functions between all technical facilities of the BMCS.

The organizational and technical principles aim at the selection of an optimum way of introduction of new forms, methods and technical facilities of management control. According to these principles, five steps exist for developing and introducing the BMCS:

(1) assessing the existing management control structure, technical facilities, mathematical methods and programs, and thoroughly analyzing the flows of working papers and information available to independent elements in the chain of command;

(2) working out and approving the BMCS development proposal which describes all the main steps involved in the development and introduction process and gives precisely determined characteristics of the employed economic and mathematical methods, technical facilities and information flows;

(3) designing the BMCS at the sketch level to set up more detailed and concrete system specifications and using the development proposal data to determine the specific features of the main steps of the development and introduction process;

(4) designing the BMCS at the working level to determine standard-and-reference indices and codes of all types of data maintained in the BMCS and obtain working drawings and programs by using the sketch-level design data;

(5) introducing the first section of the BMCS.

The main element of the BMCS is the regional control board (RCB). The power system incorporating all electric stations, and thermal and electric networks, located within the boundaries of a given territory and utilizing a common production process, is considered to be a complex power undertaking. The RCBs are intended to perform all functions concerned with power system management and control and are equipped with repair and auxiliary subunits; note that RCBs utilize the principle of operational economic autonomy (also known as the principle of self-supporting economy). One of the most important tasks concerned with the improvement of power system management and control is the integration of power systems and improvement of the operational economic autonomy principle.

Power system management and control at the medium and high levels of command hierarchy is effected in accordance with the regulations approved by the USSR Ministry of Power Industry. There are republican ministries of power industry and electrification in the Ukrainian, Kazakh and Uzbek Soviet Socialist Republics. The power systems of the RSFSR regions are under control of the Main Operational Control Boards of the USSR Ministry of Power Industry. The power systems of the other republics are under control of their Main Boards of Power Industry and Electrification, which are also subordinates of the USSR Ministry of Power Industry (except for such board in the Moldavian SSR).

The structure of the dispatch control in the USSR United Power Grid. As stated above, power system dispatch control is based on the territorial-hierarchical principle.

The responsibility for the economic and operational dispatch control of every power system lies with the regional control board. Responsible for the economic control functions are the Main Operational Control Boards as well as the Main Boards of Power Industry and the Ministries of Electrification of the Ukraine, Kazakhstan and Uzbekistan. On the other hand, it is the responsibility of the area-level control boards to perform the operational dispatch control functions.

The coordination and management of operational dispatch control activities are within the scope of the USSR United Power Grid Central Control Board, which also has control over the economic activities performed by the area-level control boards.

The USSR Ministry of Power Industry has a number of construction/erection trusts of the union subordination, which are responsible for the construction of thermal and atomic power plants, transmission lines and substations, and also for the erection of thermomechanical and electrical equipments. There are also specialized boards responsible for the construction of power complexes and industrial enterprises relating to the other branches of the national economy.

The construction/erection trusts are under control of the Main Industrial Boards of the USSR Ministry of Power Industry.

Therefore we may note two main fields with which the subordinates of the USSR Ministry of Power Industry work:

management of capital construction (including power installations constructed in the Soviet Union and abroad, and industrial enterprises); and also management of industrial enterprises relating to construction industry, power installations maintenance and repair, and machine building industry;

management and control of electric and thermal power systems.

Under the 10th five-year plan, the introduction of the first section of automated management control systems was planned so as to provide for management at differing levels of authority as follows:

the ENERGIYA branchwise management control system (BMCS) comprising two main specialized bodies working correspondingly with the two main operational fields above, and nine functional subsystems that deal with the activities of industrial ministries.

the automated dispatch control system (ADCS) intended to implement dispatch control of the USSR United Power Grid and of interconnected power systems;

automated management control systems for power system Undertakings (PSU AMCSs);

automated management control systems for construction erection trusts (CT AMCSs) intended to solve the problems of economic and operational control concerned with construction of power installations and industrial enterprises;

automated management control systems for large electric stations; and

automated management control systems for large units of thermal power plants.

The subsystems of the ENERGIYA system. The nine, branch-oriented, subsystems cover management and control of the following operational fields:

perspective development of the branch;

technico-economic planning;

finances;

planning, record keeping and study of labor and wages and salary;

supply of materials and machinery, process equipment, construction materials and mechanisms, and fuel;

planning, record keeping and study of personnel;

research and technical project work, scientific-technical information;

accountancy;

transport operation.

A specialized subsystem established for the management and control of capital construction, construction industry enterprises, and other industrial enterprises effects the following:

technico-economic planning and study of contract activities;
operational control of construction activities;
technico-economic planning and study of construction industry;
operational control of industrial undertakings; and
control of sales activities in construction industry.

The automated management control systems belonging to all levels of command hierarchy except for the lowest ones are complex integrated systems intended to solve in the aggregate the problems of production and organizational control.

The tasks of operational dispatch control. These tasks are within the scope of the automated dispatch control system (ADCS), which is part of the subsystem of the ENERGIYA system responsible for management and control of electric and thermal power systems.

A power system treated as a controllable object has the following characteristic features:

continuity of processes in which electric energy is produced, distributed and consumed;

rigidity of interconnections established in a single production process encompassing a large number of electric stations distributed throughout a vast territory of the country;

occurrence in the time of emergency of transients that tend to develop and spread over a large territory instantaneously.

There are four planning control processes which are typical of dispatch control and related to different time levels:

current (long-term) planning dealing with the prediction of demand month(s) to year ahead;

short-term planning dealing with the prediction of demand day(s) to week ahead;

real-time automated control;

automatic control.

The ADCS is a complex including personnel, technical facilities, and economico-mathematical methods ensuring the solution of the main management and control problems concerned with the United Power Grid and interconnected power systems;

The ADCS is an integrated system that incorporates the systems as follows: an automated production process planning system (APPPS) used to solve the problems of long- and short-term planning, and an automated production process management control system (APPMS) used to solve the problems of automated real-time control and automatic control.

The automated management control system for power system undertakings (PSU AMCS) is an integrated system that incorporates the ADCS, and an automated organizational control system (AOCS).

Like the analogous systems in other branches of industry, the AOCS is a complex including personnel, technical facilities and economico-mathematical methods, which help to solve, at all time levels including planning, the problems of organizational (administrative) management and control.

The ENERGIYA system may also be described as an integrated system comprising an automated organizational control system (AOCS), a construction activity management control system (CAMCS), and the USSR UPG ADCS at the highest level of command hierarchy.

At each level of control, the CAMCS and AOCS are analogous to those management control systems which are functioning or being developed in construction industry or in extractive and transport branches of the national economy.

During the 10th five-year period, the development of CAMCSs and AOCSs was planned to be based on the second generation computers. Between 1974 and 1975, the third generation computers of the EC Unified System of Computers were introduced into power system management and control.

The ADCS may be considered as a system most typical of management control entities in the power industry. At all levels of command hierarchy, ADCSs should be developed by using, in the aggregate, the means of automation, telecontrol, communication and computation. There are three stages of development work as follows.

In the first stage of the ADCS development based on the second generation computers, the functions involved in operating conditions planning were automated.

Dozens of digital computers, mainly those belonging to the second generation, were used at the levels of control referred to the USSR UPG Central Control Department, area-level control boards, and some large power systems. The software devised for these computers enabled an automation of most important and cumbersome computations. The algorithms and programs were basically developed in research institutions, and many specialists from the CCD and area-level control boards contributed to this work.

Used on a wide scale were the programs dealing with load forecasting, computation of steady-state conditions, optimization of operating conditions in terms of real and reactive power, computation of short-circuit currents, transient stability, planning of series operation of hydropower plants.

Thus, the use of the above computers for dispatch control made it possible to solve all main problems concerned with planning of power system operating conditions. These computers, however, failed to tackle the tasks that require real-time means for data input-output, display and recording.

The second stage of the ADCS development is characterized therefore by the employment of the third generation computers and modern means of data gathering, transmission and processing. This allows the control engineer to maintain the operating conditions of a power system by using the ADCS as a consulting facility. As a result, digital computers will operate in conjunction with the operational control loop and produce data with which the control engineer is able to ascertain the present or predicted operating conditions. With such an equipment the control engineer is given options which would help to solve, in the first place, the problems of collection, transmission, reception, primary processing and display of data representing dispatch control chores.

To provide for effective dispatch control, the maximum permissible delay time should not exceed the total time during which the required data is collected, transmitted and received and the responsible decisions are then made to determine adequate strategy of control, plus the time during which the control signals are applied to and executed in the controllable power objects. The *maximum permissible delay time* refers to a time interval taken for the technico-economic variables depicting system operation to vary during a non-controllable process by the amount not in excess of the permissible deviations from the optimum operating conditions in terms of system reliability and economy. Note that the amount of variation also depends on the source data and on the adequacy of calculation techniques employed.

The control actions on the power systems in both normal and abnormal conditions are beginning to be automated in the third stage of the ADCS development.

The ADCS of the USSR UPG is designed and constructed by taking into account the existing hierarchical structure of dispatch control in which a lower level of the command hierarchy is under close control of a higher level.

The USSR UPG ADCS includes the following units:

the computing centre of the USSR UPG CCD;

the zonal computing centres of the area-level control boards;

the computing centres of power systems and automated management control systems of power stations and district-level networks.

The technical facilities of the above computing centres must include:

computing devices used to solve problems involved in operational dispatch, industrial and economic control activities;

devices for acquisition and transmission of telecontrol and alphanumeric data;

data display and tabulating devices; and

auxiliary devices for copying and printing data records as well as clerical aids.

The analysis results show that the development of self-contained computing centres in the near future is worthwile only for large power systems with critical operating conditions. Thus the ADCSs of the area-level control boards must be devised by using the principles of centralization and decentralization. This means that in the case of small power systems, for which their own computering centres are not advisable on economic grounds, all computations are to be carried out at the computing centre of the associated power interconnection on the basis of time sharing principle. On the other hand, in solving the problems of control of the interconnection operating conditions, large power systems having their own computing centres should be given a small degree of particularization sufficient for determining those main variables and constraints on a power system at which the interconnection as a whole has the most favourable technico-economic indicators.

The technical facilities of computing centres must provide for the solution of all problems at the respective level of management within the scope of the ENERGIYA system. These problems, including long- and short-term planning, can be broken down into two large groups as follows: one embracing real-time control functions, and the other dealing with functions relating to processing, display and recording of the pertinent data.

The two groups of problems are of utmost importance to the three higher levels of dispatch control (CCD, area-level control board, and a power system) where the occurrence of such events as equipment failure or a deferred decision might result in a considerable loss of national product, or insufficient customer load. It is feasible, therefore, to divide computational means available to each of the above levels into two entities having a common information program support basis: a computer complex (CC) used to solve dispatch control problems related to long- and short-term planning and also economic and industrial-technical problems involved in the field of the power industry; and a real-time computer system (RTCS) intended for reception, primary processing, display and printing out of relevant data and also for solving the problems of real-time control of power system operating conditions.

This approach to the situation allows the computational means to be employed in a very reliable and efficient way and two aspects are critical in this connection.

Firstly, the above division makes it possible to use computers in the CCs and RTCSs that differ from one another in their architecture, composition, operational capability, functions, and software, and to expand, modify or replace the computers easily.

Secondly, the reliable operation of the computers is achieved at a greater economy, since the complete redundancy principle is applied in this case only to the real-time computer systems while

the computer complexes utilize conventional universal computers of the desirable size. The computers of all levels of management have a typical architecture, thereby providing for an effective use of building-block and plug-in principles widely applicable to the third generation computers. Under these circumstances, the computing centres belonging to the different levels of management but having the same structure will differ from one another by their size and composition of data input-output, display and recording devices. This allows for the preferred use of a number of compatible digital computers of the third generation from which computing systems of the required operational capability can be formed.

All problems dealt with in real-time computer systems may be classified into three groups as related to computer operation reliability:

reception and processing of incoming data;
display and recording of data; and
real-time control.

The problems involved in the first and second groups above call for increases in computer reliability requirements since the absence of valid data makes control actions ineffective and must be considered, therefore, as a failure of the real-time computer system as a whole.

Analysis data show that the required validity of data obtained in solving the problems of the first and second groups is achieved by using not less than two digital computers belonging to the third generation. On the other hand, the desirable validity of data characteristic of the problems in the third group is provided by one digital computer of the appropriate operational capability. On the basis of the analysis of the existing computers and those computers which are under development, we may conclude that the most applicable to the solution of the problems of the first and second groups are digital computers type Videoton-1010B, M-6000 and EC-1010, and that the problems of the third group can be handled by the computer type EC-1030. At present, there are two typical computer-based schemes devised for the real-time computer systems at different levels of management:

a first scheme used in the real-time computer system of the computing centre of an interconnection comprises two (or three) digital computers type M-6 000 or two digital computers type Videoton-1010B operated in conjunction with one (or two) digital computers type EC-1030; and

a second scheme used in the real-time computer system of the computing centre of a power system comprises two (or three) digital computers type M-6000 and one digital computer type EC-1020 or EC-1030.

The implementation of the above schemes depends on the stages

of system integration and the number of tasks to be tackled. In the real-time computer system, the peripheral equipment and some functional units must be provided with standby devices. In the event of the complete failure of the RTCS, a backup equipment including mimic diagrams, control desks, pointer-type indicators must be available to display the real-time telecontrol data, and the control engineer must be able to communicate with the computer complex in order that the principal real-time tasks will be implemented.

The computer complexes at all levels of management must be allowed to expand their operational capability to accommodate the increases in the size and complexity of the problems being solved, in the number of users available, and in the structure of an expanding data acquisition system.

During the 10th and 11th five-year periods, digital computers of the third generation, types EC-1020, EC-1030, EC-1040, EC-1050 and EC-1060, were planned to be introduced into power system management and control.

The facilities of the ENERGIYA system used for acquisition and transmission of telecontrol and alphanumeric data should fit higher reliability and accuracy criteria with the number and length of communication channels kept at a minimum.

To collect and transmit real-time data on network configuration and power system operating conditions, use should be made basically of pulse-code telemetry systems whose signals carrying a large number of different messages are sent on standard-type multiplexed telephone channels. The construction of the transmitting circuit and the amount of the transmitted measurands depend on the form of hierarchy of dispatch control. The information model of the network should be formed which is indispensable for the solution of all real-time and planning problems involved in dispatch control activities.

Provision should be made for transmission of control action signals from the real-time computer system of a computing centre to the controllable objects (stations and substations) which are responsible for automatic load-frequency control and automatic voltage control as well.

The reliability of the telemetered data representing the control actions must be high.

In the initial stage of development of the ENERGIYA system, telegraph printers would be used on a wide scale for transmission of alphanumeric data. Further development would imply the use of data transmission devices to transmit the data over the conventional telephone circuit at 600-1 200 baud rate; in this case, telegraph printers would be operated as standby devices and would transmit some specific types of information.

Telecontrol data are input to the computer and control action

signals are output from it automatically by using interface devices which provide the incoming and outgoing information with addresses, with the result that some part of work burden is removed from the central processing unit.

Important to the ENERGIYA system are peripheral equipment capable of displaying, tabulating and plotting data. There are three basic groups of this equipment belonging to the dispatch control personnel of power systems and interconnections; the personnel of the subunits of the ENERGIYA system who are engaged in the management and control of construction and industrial-economic activities in the power industry; and the personnel who are engaged in the maintenance of technical facilities and also in the development of software for the ENERGIYA system.

The reliability of the equipment of the first group above must be as high as possible. In addition, the equipment should display and plot on a substantially real-time scale very illustrative and diversified data representations, both alphanumeric and symbolic-graphical, available in considerable amounts. Data display means for presenting relevant information to the control personnel are installed in control rooms and may be either general-purpose or individual.

The group-use data display means are as follows:

a wall diagram (also known as a system diagram display board or mimic diagram) showing all circuits on the interconnection and presenting the network device status indications;

a projection-type or visual display board showing real-time representations of the diagrams of certain power installations and any desired portions of an interconnected power system;

a large light annunciator showing real-time representations of switch positions in the network of an interconnected power system or producing indications on the deviation of the present operating conditions (real power, current, frequency, voltage) from the scheduled values.

There are the following individual data display means:

CRT display units to show deviations from the scheduled values of electric variables; connection diagrams of stations and substations, whose state corresponds to the given and the preceding point in time, with the current values of the variables of interest; any desired part of network configuration; alphanumeric representation of process data and statistics; reference-instructional data, including ratings of basic equipment, settings of relay protection schemes and emergency automatic control schemes, directions calling for the various operations such as switching on and off the equipment, eliminating contingencies, and the like;

small light annunciators for presenting to the control engineer, on demand, certain electric variables of interest (real and reactive power, current, voltage, or frequency);

analog and digital indicators showing certain electric variables of interest;

selectors showing reference-instructional data.

To print out real-time dispatch control data and also process and statistical data, control rooms are equipped with the following: alphanumeric printers; X-Y plotters; electrically driven typewriters.

The data display means of the second group of peripheral equipment include CRT display units showing alphanumeric data. To print out large amounts of data, use is made of alphanumeric printers. Small amounts of data such as reference records, tables, and summary lists are printed out by means of electric typewriters.

The third group of peripheral equipment includes data display and printing means capable of handling alphanumeric and symbolic-graphical data; among them are CRT display units showing graphical and alphanumeric data, electric typewriters, alphanumeric printers, and X-Y plotters.

The software of the ENERGIYA system should be developed by using data on the architecture and specification of the hardware available. It consists of two program sets as follows: the system program set whose components provide for the most effective and secure use of the given hardware configuration and of the functional links of management and control; and the application program set whose components make it possible to solve the problems of planning and management and control of the power industry.

The system program set includes the following main components:

the operating system designed to support multicomputer systems at all levels of management and provide for their joint operation when using real-time, batch-processing and time-sharing modes;

the library including higher order algorithmic languages compilers and computer-oriented autocode-type languages;

the standard-type subroutine library whose components provide for calculating standard functions and making the most frequently encountered conversions;

the utility program library whose components execute, in a convenient and effective way, input-output operations and the editing of the programs being run and the original data;

the maintenance program library whose components are used to check the functioning of all devices and units of the hardware so as to provide for the remedying of the detected troubles as quickly as possible.

The application program set includes the following main components:

the library of programs used to provide all levels of management with relevant data;

the library of programs used to implement operational control of the power industry; and

the library of programs dealing with long- and short-term planning.

The original computer applications to dispatching were made to solve some specific problems such as determining steady-state conditions, real power forecasting, and the like. However, modern practice in this field concerns the development of system-oriented application programs capable of solving integrated problems involved in automated dispatch control.

In order to employ to the fullest extent the versatility of such programs, it is feasible to develop the software of the ENERGIYA system in such a manner that a maximum number of the existing algorithms and programs will be implemented on the basis of modular structure. Thus combining separate modules in a unified fashion and changing dynamically their number and composition help to solve effectively many integrated dispatch control problems.

2.9. Organization of Dispatch Control in the Soviet Union

Being part of the ENERGIYA branchwise management control system, dispatch control bodies are responsible for reliable operation of the USSR United Power Grid in the most economical manner. The origins of the operational dispatch control in the Soviet Union can be traced back to the start of the 1930s. The present-day structure of power system dispatch control is shown in Fig. 2.12. We can see that it is based on a hierarchical principle, with a lower level of the command hierarchy under close control exercised by a higher level of that hierarchy. The USSR United Power Grid Central Control Department (UPG CCD) is at the highest, nationwide, level. Just underneath it is another level from which area-level control boards (ACBs) effect control of interconnections or interconnected power systems. The third level of the command hierarchy as viewed in descending order is connected with regional power systems. The latter are under the supervision of the dispatch departments of the regional control boards (RCB DDs) whose subordinates are the operations personnel of the state district power stations (SDPSs) and hydropower plants (HPPs) and also the personnel of the control centres (CCs) of power undertakings and district-level networks.

The operations personnel of large and essential stations and substations are often under immediate control of the respective area-level control board. At present, the second level of the command hierarchy deals with real-time dispatch control only. The functions of administrative-economic control at that level are accomplished by the main territorial boards of the USSR Ministry of Power Industry and the republican ministries and main boards of power industry and electrification, independent of the area-level control boards.

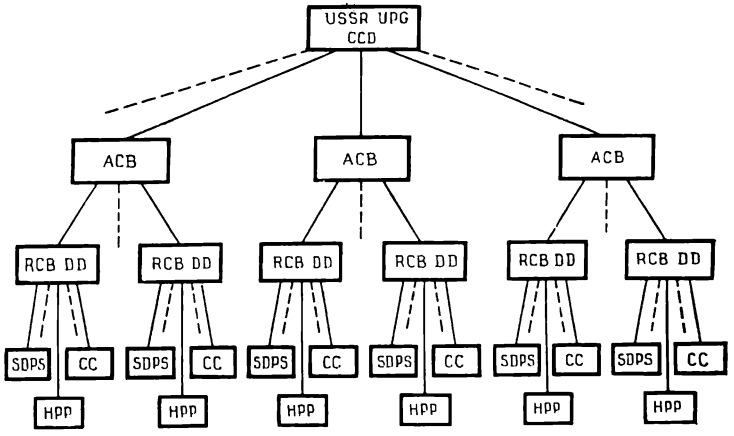


Fig. 2.12

In many cases, power systems and interconnections operate in parallel through the use of networks of complex configuration. Moreover, they include different types of electric stations and tie lines. Under these circumstances, much more responsibility for maintaining the power balance rests with the operational dispatch control bodies and the most important among them are the USSR United Power Grid Central Control Department, area-level control boards, and dispatch departments of regional control boards.

The ACBs are self-contained bodies which are under administrative supervision of the CCD. There are a number of departments in the CCD and ACBs that deal with dispatch control, power system operating conditions, hydrotechnics, relay protection and emergency control, dispatch and process control, communications, future trends, computers, etc.

Being part of the regional control board, the dispatch department usually includes the dispatch control section, operating conditions section and statisticians section. The RCBs also include other units dealing with relay protection and emergency control, communications, etc.

A rota of three shifts operating on the round-the-clock basis are formed from the operations personnel of the ACBs and RCBs to effect control on a power system. In the ACB (or CCD), one shift usually consists of 3 men as follows: the senior control engineer, control engineer, and an operator (or statistician). In the RCB DD, one shift includes 2 men: the senior control engineer and control engineer.

The shifts operate in control rooms. The control engineer's working place is equipped with a control desk having a telephone switch-

board and telemeters. The control desks face the system diagram display board (wall mimic diagram). In the Soviet Union, most of mimic diagrams are animated and use telemetry data to present the actual switch positions by means of light indicators. The most important measurands such as intersystem power flows and frequency are input to recorders.

In the power systems having power flow governing or limiting facilities, the control engineer's control desk is fitted with a control panel used to perform the appropriate control actions. Many mimic diagrams utilize CRT display units. To receive telecontrol data and control CRT display units, use is made of minicomputers type M-6000 and Videoton-1010B. The maximum diagonal size of CRT screen is 59 cm.

CRT display units are used to display the desirable regions of a network (either detailed or summarized representation); here telemetered load flows and voltage levels are shown along with clear text messages, including data on the power system status (for example, the "off" switch positions and the like).

Quite recently, the CCD has put in service a new control centre equipped with a large group-use computer-controlled light annunciator to present the data mentioned above. It is manufactured by the Videoton Company (Hungarian People's Republic).

The hierarchical structure of dispatch control proved to be useful and will be therefore applicable to further development work on the Grid.

The control responsibility is divided among the personnel at different levels of the command hierarchy, which provides for the implementation of adequate control of power systems and interconnections, thereby providing for their normal operation and rapid elimination of contingencies.

The duty control engineers monitor the main network configuration, check for proper power system operating conditions and introduce the necessary corrections. The main duties of the control engineers at the CCD and ACBs are to allocate power among interconnections and power systems, regulate intersystem power flows, control frequency, check the "on-off" positions of the switches and the settings of the emergency control schemes for the main intersystem tie lines, supervise the accomplishment of the operations on the equipment that is under their control and also the operations concerned with elimination of emergency cases occurring in interconnections and power systems, effect control on the activities of their subordinates at the lower levels of the command hierarchy and render them help, if necessary.

Thus the dispatch control bodies must operate to ensure:

the solutions to the problems of consumer demand, both electric and thermal, and peak-load supply;

the continuity of supply of electricity and secure and reliable operation of the whole power system and its components;

the standard quality of electric and thermal energy as assessed in terms of scheduled values of grid frequency, network voltage levels, temperature and pressure of steam and hot water delivered to consumers;

the operation of the grid as a whole and interconnections in the most economical manner, while maintaining the energy resources consumption rates at a minimum;

the solutions to the problems of eliminating as quickly as possible the disturbances in power system parallel operation and maintaining power system survivability by which is meant the ability of a power system to resist cascading.

To place the performance of the above functions of dispatch control on a secure basis, it is necessary to estimate power system operating conditions by using load prediction data obtained from records and corrected for an expected growth of the industrial production relating to the current year. With the projected load determined, the following items of information should be produced:

an annual schedule depicting monthly peak loads on a power system and provision thereof, taking into account seasonal variation, outage periods for major equipment, and conditions in which reserve capacity and intersystem power interchange are provided;

annual, quarterly and monthly electrical energy balances, taking into account intersystem flows of electrical energy;

documents dealing with optimum allocation of loads among stations, power systems, and interconnections;

daily schedules depicting active loads and spinning reserve;

diagrams of electric connections existing on major network;

calculations of real and reactive load flows through reference nodes of power systems, interconnections and the grid, relating to the annual peak load period and summer months; and

calculations of stability criteria, design parameters and settings of emergency control schemes.

A larger part of the information is dealt with by the staff of the operating conditions departments of area-level control boards and operating conditions sections of regional control boards. The hydrotechnical departments of area-level control boards are responsible for the solution of many important problems. Using river flow forecasts obtained from the USSR Hydrometeorological Service, they determine reservoir storages and their decreases and relationships between water resources of series of hydropower plants and water undertakings relating to irrigation, navigation and fishery.

To obtain adequate solution to the integrated problem of regulation of river flow, it is necessary to have a single management and control organization that gathers and handles on a centralized basis

data about water passage, use of water resources in the interest of power industry, and about operating conditions of hydropower plants, and also takes into account the needs of all water users. In the case of the Volzhsko-Kamsky series of hydropower plants, such an organization is the USSR UPG CCD while other such series are to be served by the respective area-level control boards.

The long- and short-term planning of consumer demand (in terms of both power and electrical energy), the determination of the desired energy resources, and the optimum real power dispatch are carried out in accordance with the existing hierarchical structure of dispatch control. The CCD provides major hydropower plants with their load schedules and produces the total load schedules to be used by pool-level control boards. Using the data received, the ACBs work out load schedules for the most powerful and essential stations and also for regional control boards. Finally, the RCBs prepare load schedules for those electric stations over which they have control.

Thus the principal optimization problem—allocation of real loads—is answered by decomposition within the Grid in accordance with a hierarchical principle. Nonetheless, this problem is considered as appreciably complex and its solution requires extensive use of computers. In the mid-60s, most of area-level control boards and many regional control boards were equipped with the second generation computers type M-220 (M-222) and LCM-4 which were used to perform the above calculations, including the most important ones relating to daily load schedules. At present, the third generation computers types EC-1030, EC-1040 and M-4030 are being introduced into dispatch control. Planning of new computer schemes involves the combining of the third generation computers with on-line mini-computers. As a result, computer systems will be formed which can be used as consulting devices for the control engineer.

The personnel of the relay protection and emergency control departments of area-level control boards adjust the relay protection and emergency control schemes existing on major intersystem tie lines. They operate in conjunction with the personnel of the operating conditions departments to determine the operation sequence of controlling frequency, voltage and power exchange.

Providing reliability of service from a power system greatly depends on factors relating to planned and unplanned outages. For equipment under direct or co-ordinate control of an area-level control board (or the CCD), planning a maintenance program obeys a hierarchical principle. In this case, the duty of the area-level control board (or the CCD) is to produce maintenance work schedules, for use by regional control boards, covering the four seasons. In the RCBs, these schedules are tied up with the actual units and facilities. The management personnel of the ACB (CCD) and RCB must okay the plans at least one month before the coming year.

The withdrawal of plant for maintenance or activation of standby items (whether or not the okayed plans are available) is implemented through the use of work orders presented by the management personnel of the installation to the dispatch department of the regional control board. In the case of the equipment under direct or co-ordinate control of the ACB or CCD, the regional control board presents the received work orders to them.

The work orders relating to the withdrawal of plant for maintenance may be accompanied with preventive maintenance orders requiring disconnection of relay protection schemes, automatic control systems and telecontrol devices for adjustment and test work to be accomplished.

The authorized organizations are allowed to receive work orders merely during the specified periods of a day. The work orders are then handled to determine system operating conditions resulted from the particular component outage or tripping and to assess the applicability of such operating conditions to a power system.

The work order handling process is complex and laborious. Thus the work orders requiring intricate switchings and critical changes in system operating conditions must be passed to the authorized organizations 3 days before the commencement of the work. There are, however, forced outage (tripping) orders dealing with unplanned maintenance or test of the equipment. Such orders are allowed to be passed directly to the control engineer at any time of day so that he can handle them until the end of his shift. The deferment of the forced outage orders requires the permission of the senior control engineer of a power system, area-level control board, or the CCD.

To continuously keep a power system in normal operating conditions, the operations personnel must be provided with instruction manuals that describe their duties, operation sequence and links between different levels of the command hierarchy. The most important operations relating to changes in network configuration, methods of controlling system variables, and use of automatic control and relay protection schemes must be assigned priority levels. The operation manuals must contain technical specifications and reference data as follows: stability limits for intersystem tie lines; permissible network configurations and system operating conditions; maximum and minimum plant generation, and the like.

The relevant operation manuals and forms are to be worked out and accepted by persons in charge in all bodies of dispatch control in accordance with the scope of the work to be accomplished at respective levels of the command hierarchy.

The dispatching chores are not a sole responsibility of the CCD, ACBs and RCB DDs. They are involved in planning of new power systems and of extension of existing systems; in forming of new

interconnections from power systems and of extension of existing areas; and in commissioning new electric stations, transmission lines and other system components. In addition, they work out development proposals for automatic control schemes to keep a power system in normal operating conditions and also system-oriented emergency control schemes. Finally, their work on existing automatic control equipment concerns testing, putting in service, selection of settings, and study of the performance of the equipment.

There are a number of activities performed by dispatch control boards and departments in connection with different operating conditions existing on power systems such as autumn and winter peaks, flood periods and the like, and also with the commissioning of new installations. These activities are as follows: the development of the working network configurations and system operating conditions to fit normal operation criteria; the selection of optimum voltage levels at the nodes (reference points) of a major network; and the improvement of the grid reliability factors, including the consideration of operational economics.

To use the energy resources in the most economical manner, the dispatch control boards and departments participate in the study of the fuel situation in the market and the development of consumption programs for different types of fuel.

The dispatch control boards and departments take the part of coordinators and in some cases of direct participants in research and development work and testing of equipments that ensure a more reliable and efficacious way of operating power systems and help to improve dispatch control.

Important to the CCD, ACBs and RCB DDs are activities concerned with the gathering and processing of data on the status of the grid, interconnections and power systems. In addition to data assisting the control engineers in making reasonable real-time decisions, a great deal of day-to-day information is hanlded which depicts system status relating to the previous day including such parameters as generation capacity, peak load, power interchange, water level in major reservoirs, amount of fuel, and the like. The dispatch control bodies gather periodically data that serve to study system operating conditions and availability of plant and check the fulfilment of planned tasks. The data are used to meet the needs of both dispatching and administrative-economic management and control.

REVIEW QUESTIONS

1. What is the principal goal to be attained during dispatch control?
2. Describe the essential features of dispatch control in countries with publicly owned utilities.
3. Describe the major structure of dispatch control bodies in the Soviet Union.
4. What is meant by the terms primary, secondary and tertiary regulation?

What is the function of these types of regulation employed in dispatch control?

5. Describe the major functions and types of automatic control schemes designed to control power systems.
6. What is meant by the term power exchange? How does the dispatcher control the exchanged power?
7. What considerations are to be chosen to provide for optimization of power system operating conditions?
8. Describe a turbine-control block diagram and its basic characteristics.
9. What are the essential features typical of dispatch control of voltages existing on electric networks?
10. What are the system-oriented foundations of the branchwise automated dispatch control system ENERGIYA?
11. What is the structure of the USSR dispatch control bodies?

Chapter 3

Data Display Facilities of Automated Dispatch Control Systems

3.1. Visual Displays. Means and Methods

The number and the type of data display facilities incorporated in the automated dispatch control system (ADCS) depend on the requirements to be met by data representation system of the ADCS. Practically all existing data display methods can be used which, together with the technical facilities of ADCS, provide a single, the most useful way of handling data at each level of the command hierarchy.

To select properly the type and number of data display facilities, the following should be taken into account: the content of information-oriented and specific power engineering tasks and the periodicity with which they are to be tackled; the operational and program-associated capacities of the employed computers, telecontrol facilities and data transmission systems.

The ADCS data display facilities can be of individual or group-use. The individual data display facilities include pointer-type and digital devices, light annunciators and CRT display units located in the vicinity of the control engineer's working place. The main group-use facility is a wall diagram (also known as a system diagram display board or mimic diagram). It shows control data in such a manner that all the operators in the control room can perceive it promptly and unambiguously.

The individual and group-use data display facilities are divided into active and passive. The passive facilities display only specific types of data whose form, size and sequence are known. Mimic diagrams may also be grouped with the passive data display facilities, since the presented data can be varied in content, size and form only when the mimic diagram is modified, i.e. the number of panels, the number and type of measuring instruments, etc. are changed.

Unlike passive facilities, active ones can display different types of data and correct and edit them in terms of their form and contents,

a feature important to man-machine systems to which the ADCS belongs.

A typical active data display facility is a CRT display unit, described in the following section.

As a media to present the visualized data to the operator, use is made of the following: screens of CRT display units; screens of projection-type boards using reflected or transmitted light; screens made of fluorescent elements of different shape such as rectangles, squares, special-purpose symbols or symbolic elements, digits, letters, etc.; screens built on the so-called liquid crystals. In addition, use is made of matrix-type screens, in which each element of the matrix can have two readily distinguishable luminance levels. The matrix elements can be implemented in the form of lamps (fluorescent, glow-discharge, incandescent and others), light-emitting diodes, and cells having two surfaces of different colours, the required surface being activated by means of an electromagnetic relay.

In those cases when each matrix element can produce or reflect several colours (for example, red, green and blue), it is possible to obtain colour images. The working field of matrix-type screens may be uniform or may comprise separate character positions (submatrices). The character-position screens are usually used to show alphameric data. The uniform screens can present both alphameric and graphic data.

Data can be presented and registered on conventional and special-purpose paper or film, on which the desired image is drawn, printed out or developed by using mechanical, electrostatic, chemical or other methods. For representing calculation results in the form of graphs, say curves of consumers' demands, dynamics of the variation of operating conditions in transients, network diagrams and others, use is made of different types of graph plotters in ACDS. The plotter has writing head with a pen (stylus), which describes the required plot, diagram, etc. in the coordinates supplied by the computer.

In certain graph plotters, the writing head moves only along the lateral axis. In this case the longitudinal movement of the head is replaced by the corresponding movement of the paper. The head has several styluses, as a rule; this allows the drawings and diagrams to be produced in different colours. Alphameric signs and messages are drawn by the head as per special-purpose subroutines, or use is made of a printing head for the purpose. Low data output speed is the main disadvantage of the graph plotters. Electrographic copying machines, operating in conjunction with CRT display units are therefore used to obtain hard copies.

Wide use is made of data display boards made of different materials (plastics, metals, wood). In such boards, the information to be displayed is in the form of separate elements: letters, digits, characters, segments of straight lines, etc.

The data display devices are characterized by a number of special features.

Data output speed is of significant importance for the ADCS when the information is to be displayed in real time, i.e. as soon as it enters the device. Real-time data display can be ensured only when the volume of information delivered to the facility input per unit time does not exceed the data output speed. Therefore, in the devices intended for displaying real-time data, the data output speed should be selected with due consideration for the maximum possible data input rate.

Versatility characterizes the possibility of displaying different types of data (plots, diagrams, alphameric characters, special-purpose symbols) combined in formats different in their content and size.

The resolving power of human eye equals 1′, approx. With the observation distance equal to 45 cm, the human eye can perceive an image of size about 0.125 mm. The minimum distance at which all images are fully perceived is generally equal to the image width. In this case, about 1000 lines per screen height ensure proper recognition of the image. The resolution of a data display facility is therefore considered adequate if about 1000 elements (points), along the vertical of the screen (frame), are perceived at a distance equal to the image width. In the general case, the *resolution* of a data display facility is characterized by the size of the smallest element used to form the image. For example, the size of the light spot is a measure of the resolution of a CRT display unit.

Information capacity of a data display facility is determined by the limit amount of data which can be displayed concurrently on its screen. It is evident that the information capacity depends on the facility resolution and the screen size (work area). When the image is formed from similar size symbols (characters), the information capacity may be estimated from the amount of available character positions.

Luminance (photometric brightness) is the ratio of the luminous intensity of the source surface element in the direction of observation to the element area projected on to the plane which is perpendicular to the direction.

Image contrast range is a characteristic used to judge the difference in the perception of two adjacent image elements. This difference may be defined in terms of luminance, color, size, shape or duration of display of two image elements being compared. However, the term "image contrast range" often refers to the difference between the luminances of two image elements. As a quantitative measure use is made of the contrast coefficient, C_c, and percentage contrast, $C_{\%}$. The contrast coefficient is the ratio of the luminance of the brightest image element to the luminance of the darkest image element. It is useful in the cases when the grey tone scale is to be reproduced.

The contrast range (expressed in percents) is usually used to characterize those data display facilities in which the background luminance level, L_{ext}, resulted from external illumination, constitutes a considerable part of the image luminance, L_{im}. Thus we have

$$C_c = \frac{L_{\max}}{L_{\min}}; \quad C_{\%} = \frac{L_{im} - L_{ext}}{L_{ext}} 100\% \tag{3.1}$$

The design and proper choice of the ADCS data display facilities usually rely on the use of the percentage contrast, $C_{\%}$, since the illuminance (illumination) of their working surfaces must be appreciably high. To provide for adequate contrast range, the screens of the facilities must have a large luminance. This means that conflicting requirements should be met in choosing lighting systems for control rooms. On the one hand, the control engineer's working place as well as the devices making use of the reflected light (mimic diagrams, measuring instruments having no illumination lamps, control and communication panels, etc.) must have an appreciably high illuminance. This, on the other hand, requires increased luminance of CRT screens, projection-type boards and the like. Of course, account should be taken of directional lighting means, shields, filters, blinds, etc. In such circumstances, a way out is to use in certain cases some trade-off of the illuminance level at which both fluorescing and externally illuminated images produce a similar effect on the observer's eye.

Color is a characteristic which depends on the wavelength of the light either emitted or reflected by a data display facility. The human eye can discern colors in the spectral range from 400 $\times$ $\times$ 10^{-9} m (violet) to 700 $\times$ 10^{-9} m (red). The human retina consists of cones and rods. The rods are more sensitive than the cones and their sensitivity is slightly shifted towards the violet end of the spectrum. The cones are responsible for photopic vision.

Visual sensation, which is produced when light falls on the retina, is characterized by hue, chroma and luminance. All these characteristics are responsible for sensation of color, i.e. chromaticness. Achromatic color, also known as neutral grey color, has no hue or chroma. Luminance is that property of the color which allows the eye to perceive it as equivalent of sensation produced by a certain set of neutral (achromatic) grey colors. Equal amounts of the luminous flux having different wavelengths do not produce equal color perceptions for standardizing photometric data, a standard curve of spectral response of human eye has been drawn. This curve, taken for the cones, determines brightness sensation (sensitivity of a man to light) as a function of wave length. The luminance of any light source can be assessed using this curve. The maximum spectral luminous efficiency of a source corresponds to a flux of a monochromatic radiation at $\lambda = 555 \times 10^{-9}$ m.

Color determination in terms of hue and chroma may be connected with their certain physical equivalents. There is a method of color determination in which the source color is compared with the reference color, both being combined to represent with a certain discreteness the chromaticness as a whole. Another method of color determination involves comparison of a given color with a mix comprising the respective number of hues taken from a set of primary colors (red, green and blue). Using color-mixture curves, one can determine the physical equivalents of hue and chroma.

Color data display facilities have an increased information capacity, wide contrast range and ensure better recognition of different objects. However, they have as a rule lesser resolution and display data at lower luminance levels. Such facilities are usually more sophisticated and expensive.

Pattern recognition is a characteristic which depends, in particular, on pattern format defined as the ratio of width to height. Although square-shaped characters can be indicated, preference should be given to formats 5 : 7 and 2 : 3. The line width should be selected in the range from 1/16 to 1/8 of the character height. It is good practice to employ thinner lines for illuminated characters seen against dark background. Of great importance is the shape of characters. The proper choice of character sizes should take into account the importance of information, the operator's fatigue, image contrast, character design features, luminance, contrast and cumbersomeness. With all the factors taken into consideration, attention is chiefly focused on the limitations imposed on the visual acuity, i.e. the resolving power of the human eye. As stated above, the resolving power of the human eye is equal to 1′. To perceive distinctly the character *E*, the angular field of vision must be at least 5′ as a minimum. Similar characters corresponding to this minimal field of vision are usually employed for determination and testing of visual acuity.

To convert the angular size of a character to its height, one must know the observation distance. There are two general cases of interest. For individual data display facilities, use is made of the standard observation distance equal to about 45 cm. When the distance between the screen of the individual facility and the observer's eye differs from the standard distance, the converted character size is corrected correspondingly.

For the standard observation distance (conforming to the angular field of vision of 5′) the minimal character size should be equal to 1.27 mm. This is, however, the perceived but not the recommended value. The latter is usually defined in terms of the recognition probability and the discernibility of characters of similar shape. As a rule, the recommended size of the character should be three times its minimum perceived size. In our case, the recommended

size amounts approximately to 3.8 mm, which corresponds to the angular field of vision of 15′.

The group-use data display facilities cannot be characterized by the standard observation distance, because their dimensions and screens as well as operating conditions vary considerably. However, for a given group-use facility, one can determine with an appreciable degree of accuracy the maximum expected observation distance and the recommended character size by taking the angular field of vision equal to 15′.

Stability of an image is characterized by maximum shift (drift) of its constituents. The relative shift of the individual elements of an image exerts maximum adverse effect on the perception and recognition of data. Slow shift or vibration of the image complicates on the whole the observation, increasing operator's fatigue. An increase in the amplitude and frequency of image vibration might lead to a condition in which one cannot perceive clear image. Maximum permissible value of image shift should therefore be always specified for each data display facility. For character position screens, the specified values usually concern the maximum permissible shift in lines (vertical shift) and in columns (horizontal shift). It is standard practice to specify these parameters in percents of the corresponding dimensions of a character position. The facilities producing highly stable images ensure the required display linearity and the absence of edge distortions.

Space pattern recognition depends on the *coding system* representing the displayed data. The quantitative measures of space pattern recognition are the speed and accuracy of discrimination and semantic perception of the code employed. The simplest coding system is an alphabet used to represent text messages. The speed and accuracy of semantic perception are determined uniquely by the speed and accuracy of discrimination of every letter of one and the same text displayed by using different formats and designs of the alphabet elements.

We see, however, that even in this simplest case there is a distinct relationship between the speed and accuracy of semantic perception and the content of displayed data. Thus it is impossible to design a universal coding system for displayed data, which would be optimum for all possible uses. When fast events are to be perceived and qualitatively assessed, it is expeditious to use a graphic coding system for displayed data. It is known, however, that plots do not ensure accurate and rapid read-out and checking of numerical data on the events being displayed.

Verbal description of the connection diagram of an electric network usually requires several times greater information than needed in the case of incidence matrix or respective picture with a set of accepted symbolic designations.

The system approach to the design and the choice of data display facilities must take into account the fact that the operator always compares information obtained from different sources. It is evident that in such circumstances, the speed and accuracy of discrimination and semantic interpretation of data displayed by a group of facilities depend in many respects on the uniformity of the used coding system and on the relative location of the facilities. The compatibility of different data display facilities may be assessed to some extent by the number and the duration of fixations of the operator's eye on to every facility, the content and amount of displayed data being selected within typical limits.

Reliability of a data display device can be assessed in terms of availability

$$K_a = T_0 (T_0 + \tau) \tag{3.2}$$

where T_0 is the mean time to failure, h; and τ is the mean time to recover, h.

The choice of type, mix and number of facilities to form a data display system of the ADCS relies on the assumption that simultaneous failure of all facilities incorporated in the system is impermissible. In the presence of a most severe failure the amount of displayed data must be sufficient for a power system to be maintained in operational control condition. Thus the system must possess redundancy in terms of both the structure and number of the facilities used. The structure redundancy is achieved through the combined use of the facilities whose information-oriented capabilities partially overlap each other. When a facility or a group of similar facilities fail to operate, the system's data display ability is reduced but is not lost completely. The second redundancy condition requires that duplication (majorization) of similar facilities be introduced into the system.

Thus the desired reliability of the data display system of the ADCS is achieved when the system uses facilities of maximum versatility. The assessment of the system's reliability must take into account the reliability of other technical facilities of the ADCS operated in conjunction with the system.

Equipment and operational costs are the indicators which are used by a design engineer to finally judge the optimality of the selected design of the ADCS data display system.

3.2. CRT Input-Output Display Units

The CRT input-output display units (IODU's) also known as CRT indicators are widely used as ADCS data display facilities due to the following advantages: versatility; ability to display real-time representations; good image quality; ability to effect man-

machine dialog in convenient and illustrative fashion. With IODU's, digital and TV data outputs are possible.

General. When data are displayed in the form of television pictures, the electron beam is deflected to build up a raster on the screen. During a trace the beam current is modulated by the video signal. Thus the data stored in computer in the digital form must be previously converted into a video signal. For placing television pictures in the computer storage, reverse transformation is necessary. The number of storage bits required in this case equals the number of discernible points in every raster line. In the Soviet Union, the television raster comprises 625 lines per frame. This means that nearly half a million storage bits are required for storage of one picture.

Modern CRT display units preferably use digital data output method with direct addressing of the beam to any point on the screen. The digital CRT display units are of two types: character-mode (alphameric) and graphic.

The working field of an alphameric CRT indicator represents a rectangular matrix. Each element of the matrix is a standard-size character position, within which any character from the available character-set is visually indicated. Data is output on the indicator screen by specifying the address of the character position and the type of character (letter, digit, special character and the like) to be displayed at that position.

The number of character positions of the screen working field in different facilities varies between 100 and 3000. The set of the accepted characters may comprise different numbers of standard and special-purpose characters. Use may be made of character sets containing several modifications of like characters differing in size, design, etc. A standard subroutine is used to control the beam movement during a trace. The process of displaying data on alphameric indicator is therefore similar to that of the conventional typewriter.

The initial setting of the beam at the required location on the screen is analogous to the movement of carriage which ensures proper setting of sheet of paper during typewriting. The display of the desired character is analogous to the selection and the pressing of a respective key during typewriting. The information capacity of an alphanumeric indicator is usually expressed in terms of character positions of the screen working field.

In graphic-type CRT indicators, the screen's working field represents a matrix of addressable points. The coordinates of a luminous point on the CRT screen are usually given in binary code on ordinate register RY and abscissa register RX. The resolution of modern display units makes it possible to obtain a working field with $512 \times \times 512$ to 2048×2048 addressable points. This requires respectively 9 to 11 bit positions in RX and RY registers.

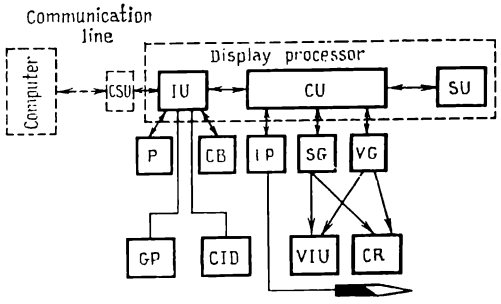


Fig. 3.1

During data display, the beam is moved in such a manner that the starting and finishing coordinates of each vector are selected. The number, length and slope of these vectors are determined by the accuracy with which the displayed data are approximated. This is a major difference between the matrix-type and the television data output methods. With television data output method, the time during which one frame is formed does not depend on the effective amount of the data being output. In the case of matrix-type method, the data output time is determined merely by the amount of useful data displayed concurrently. The information capacity of a graphic CRT indicator is therefore often expressed in terms of the maximum vector length that can be displayed on the screen.

The display of standard image elements, e.g. letters, digits, characters in graphic indicators as well as in an alphanumeric indicator can be accomplished using a standard subroutine. Unlike alphanumeric indicators, graphic indicators make it possible to produce three-dimensional pictures, to effect their rotation about any axis, to check the plots depicting variation of parameters with time, etc.

Block diagram of IODU. A modern IODU consists of the following functional units (Fig. 3.1): visual indication unit (*VIU*) comprising a cathode-ray tube (CRT) with focusing and deflection systems; control unit (*CU*); storage unit (*SU*); interface unit (*IU*); communications selector unit (*CSU*); character generators (*CG*); vector generators (*VG*); control boards with alphanumeric and control keys (*CB*).

In addition, the IODU may have additional units ensuring easy input-output, editing and logging of data.

To register data displayed on the CRT screen, use may be made of cine recorders (*CR*), graph plotters (*GP*) and printers (*P*). In some cases, coordinate input devices (*CID*) are used to simplify the procedure of read-out of scale pictures (charts, drawings and plots).

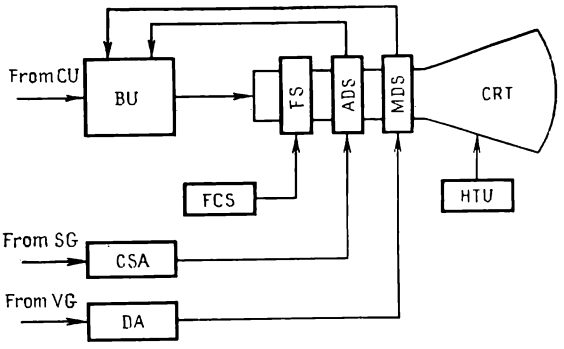


Fig. 3.2

To provide for efficient control over input and editing of data, use is made of such devices as light pen (*LP*), tracking ball, joystick, etc.

The combination of the control, storage and interface units is known as display processor which performs the following functions of the simplest computer: reception and execution of instructions available from a digital computer and control desk; storage, regeneration and exchange of data; control and synchronization of operation of all units of IODU; communication with external devices.

Figure 3.2 shows a block diagram of a *visual indication unit* comprising focusing system (*FS*), brightening unit (*BU*) for beam intensity modulation, focusing current source (*FCS*) and high tension unit (*HTU*).

To deflect the electron beam, use is made of two pairs of amplifiers working with two deflection systems. The deflection amplifiers (*DA*) are intended to set the beam at the desired point on the screen through the use of the main deflection system (*MDS*). The character sweep amplifiers (*CSA*) are designed to visually indicate letters, digits and standard characters on the screen; this is achieved by means of an auxiliary deflection system (*ADS*).

Alphameric characters can be displayed through the use of character generators or directly in the CRT by using the *shaped beam section forming method.* The character image is formed by passing electron beam through the shaped holes made in a metallic mask serving as character matrix. Such CRTs are known as shaped-beam CRTs. A character matrix usually comprises alphabet letters, digits and standard characters, e.g. full stop, comma, colon, etc. When passing through the holes of the mask, the beam takes the form of the desired character and the image of the corresponding shape is produced on the fluorescent screen.

A shaped-beam CRT comprises an electron gun, character selector deflection plates, a character matrix, compensating plates, deflection

and focusing systems. The compensating plates are used to re-direct the beam along the CRT axis after its displacement during character selection.

In some shaped-beam CRTs, provision is made for the adjustment of dimensions of the displayed characters. The character height is usually varied between 2.5 and 20 mm. The shaped-beam CRTs make it possible to produce characters with good definition and constant brightness and can be used to generate vector pictures. For this, the dot character is selected in the character matrix and the shaped beam is deflected by means of vector generators.

The shaped-beam CRT's have a number of disadvantages. For example, character generator of CRT failure requires that both the units be replaced. To change the employed set of characters, one must replace the character matrix and, as a consequence, the CRT as a whole. The use of shaped-beam CRT's is therefore connected with high operational costs though the displays using them have lesser equipment cost than analogous displays based on conventional CRTs.

The phosphor from which the CRT screen is formed, determines such characteristics of CRT display units as picture brightness and contrast, light spot diameter, decay time and information capacity. The luminescence brightness of phosphor, after it is excited by electron ray, depends also on the beam intensity, trace period, signal repetition frequency, and on decay time. The decay characteristic of phosphor follows a power or logarithmic law. When events with a low repetition frequency (below 1 Hz) are noticed, a long decay time may be necessary to make the display visible. In the case of signals having high repetition frequency (between 20 and 50 Hz), persistence smooths out the display and eliminates picture flicker. On increasing the signal repetition frequency, the persistence may turn to be very long and this will superimpose (smear) the display.

Green and orange color phosphors are used in CRT display units. The former have a short persistence and provide for a high picture brightness. They are therefore utilized for displaying rapidly varying events when the control room has relatively high illuminance. The phosphors with orange phosphorescent colors offer sufficiently long persistence (reaching several seconds); they are used in display units installed in rooms with small illuminance.

The persistence determines the desired regeneration frequency of the display. If the persistence luminance has time to drastically reduce within the period between two successive regenerations, the display is perceived as a picture which changes its luminance periodically, i.e. flicker occurs. Flicker can be eliminated with regeneration frequency of the display equal to 40-60 times per sec in the case of phosphors with green phosphorescent colors, and 5-15 times per sec in the case of phosphors with orange phosphorescent colors.

It is evident that for a beam moving at a constant velocity v the number of the displayed points N each having diameter d is determined by the indicator resolution and is inversely proportional to the desired regeneration frequency of the display f

$$N = v/df \tag{3.3}$$

It follows from (3.3) that the indicator information capacity, which is assessed in terms of simultaneously displayed characters (in alphameric indicators) or in terms of the maximum length of the displayed vector (in graphic indicators), is determined not only by the screen size and the tube resolution but also by the electron beam velocity and the desired regeneration frequency of the display.

There are cases in which improved picture perception is achieved by displaying some part of information as flicker. To this end, the regeneration frequency of the respective characters is usually reduced by a factor of 2 as compared to the normal. Evidently, the indicator information capacity may increase by the number of characters (addressable points) that appear as flicker.

The CRT indicator information capacity also depends on the number of addressable points (the number and length of vectors) used to form each character. In some indicators the data output time therefore depends on the nature of the displayed data: it is minimum when each character position indicates one point, and is maximum when each character position indicates a character whose delineation involves maximum number of points (vector sections). Note that the maximum data output time should always be less than the duration of the display regeneration cycle.

A similar situation may be encountered in cases when a CRT indicator has character positions of different size. Here the maximum data output time corresponds to character positions of higher size, which are used, for example, to display text messages comprised of capital letters.

To produce a picture of constant luminance, use is made most frequently of focusing and deflection systems ensuring constant rate and intensity of the beam current during indication of any character. There are cases, however, when increased indicator information capacity is achieved through the use of deflection systems in which the beam velocity is proportional to the desired displacement. In such circumstances, a picture of constant luminance is produced by matching the beam current and the desired displacement.

The beam current modulation is a means by which solid, dash-and-dot and dotted lines can be displayed. The desired trace thickness is selected by means of a focusing system. The width of electron beam determines the size of the light spot on the CRT screen. However, the actual size of the light spot is always more due to the light scattering in the phosphor. To obtain a high picture luminance with

a small-size light spot, it is necessary to have a highly intensive electron beam. When such a beam produces a light spot of small size, the envelope glass may crack due to local heating. The size of the light spot significantly influences the grain size of the phosphor. Fine-grain phosphors are therefore used to produce small-size light spots, which give the same picture luminance as the conventional phosphors delineating light spots of normal size.

Display processor with the instructions of specific content and structure, mainly determined by the operational capabilities of CRT indicators, is used to control input-output of data available from a digital computer. Given below is a general description of the operation of the display processor as viewed in conjunction with most of CRT indicators.

The display processor is a specialized program-control computer which reads from its storage and executes instructions responsible for the displacement and intensity of an electron beam. In addition, the display processor must provide for two-way data exchange with a digital computer, the exchange being initiated either by the digital computer or by the operator's command introduced through the display controls.

The display processor and the digital computer processor are analogous in that each has certain main registers whose state determines the processor state. In the digital computer processor such registers are, in particular, the adder and the instruction counter; in the display processor—the coordinate registers RX and RY that store data on the current position of the beam on the CRT screen, and the instruction counter that holds the identification of the display storage address at which the instruction to be executed next in time sequence is stored. The set of the operational capabilities of both the processors is more stable than the structure and content of the instructions with which these capabilities can be realized.

Practically all display processors are able to: set the beam at the required location on the screen and display (or blank) a dot; display at the required location on the screen the desired characters (in a given sequence). As to graphical indicators, they have yet another intrinsic function which consists in the construction of a vector connecting the current point on the screen with a new point. The standard characters are usually displayed automatically by using the corresponding character generator. In shaped-beam CRT displays, such generators are not used for the purpose, but the beam is moved instead of this to the required location in the character matrix.

The point coordinates can be expressed in terms of absolute values of abscissa X and ordinate Y in binary code, or in terms of coordinate increments ΔX and ΔY relative to the initial (current) point. In some indicators, the origin can change its position. There is a mode

of operation in which every point is given by coordinate Y, while coordinate X is specified by its initial value and the increment ΔX.

The additional parameters for dot, vector and text message displays may be luminance and flicker. For vectors the type of line (solid, dash-and-dot, dotted, etc.) may also be specified.

There are cases concerned with the output of text message data when the size and orientation (tilt) of each character can be specified. Sequential line scanning and transfer from the filled line to the beginning of a new one are performed automatically. In the display processor, it is possible to interrupt normal sequence of text data output by directing the beam to some other point on the screen, a procedure analogous to that performed in a digital computer processor when an unconditional branch instruction is executed. This makes it possible to make indents, align the characters with subscripts and superscripts, etc. In some cases, instruction structure allows different formats of screen working field to be used.

In addition, the display processor must provide for program-controlled access to all additional indicator facilities used to register the displayed data.

All data input-output and exchange operations should be matched with the picture regeneration cycle. Microprogramming control is often used to provide for synchronous and logical operation of all indicator units. In this case, each of the instructions described above is executed by a suitable microprogram. A set of microprograms is stored in permanent storage whose capacity is determined by the number and content of the operations to be performed and the format of the micro-instructions available. Each microprogram is characterized by the main cycle the duration of which depends on the picture regeneration period.

There are designs in which one display processor is used to control several indicators. In such circumstances, the set of instructions should be supplemented with instructions that provide for addressing, switching and servicing of each indicator.

The capacity of the display processor storage is determined by the length of the words used to describe data and control and exchange instructions and by the information capacity of the indicator. The storage capacity is usually chosen to satisfy a condition in which at least one picture can be stored at a time. In some cases, the storage capacity can hold concurrently several pictures of the displayed data.

It is possible to control data input-output by using the on-line storage of a digital computer. However, this reduces the computer operational efficiency and overloads the communications channel between the display and the computer. The compilation of the data input-output programs for CRT becomes more complicated because the operator cannot form or study images independent of the computer.

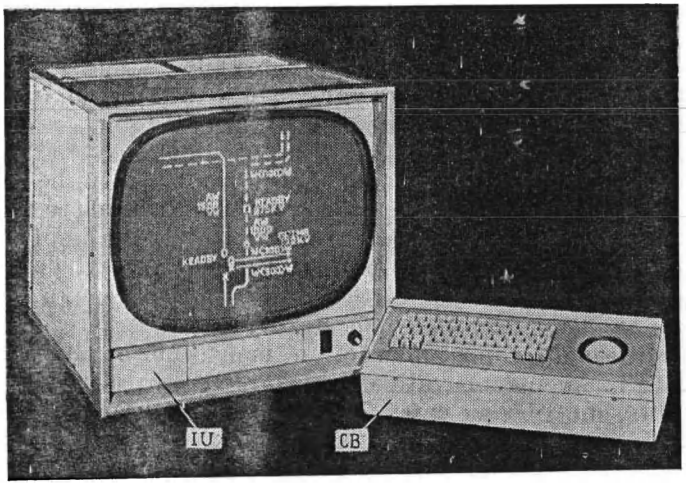


Fig. 3.3

Given below is a description of display processor MD-4 manufactured by Ferranti Limited (Britain). Its indication unit (*IU*) and control board (*CB*) are shown in Fig. 3.3.

The MD-4 has a storage unit rated for 4096 words and time cycle of 2 μs. The word format includes 24 bits. The display uses a CRT with an orange phosphor which provides for a comparatively long persistence. The diagonal size of the CRT screen is 36 or 53 cm. One MD-4 may connect up to 12 indicators MD-3. The latter differ from the former in that they have no storage unit. The maximum distance, at which the MD-4 and MD-3 may be spaced, equals about 100 m.

The indicator can produce the following displays: alphanumeric characters, special characters, vectors, and circles. Data specified by relative coordinates can also be displayed. In the character mode, 32 or 64 alphanumeric characters can be displayed.

The special characters may be displayed in two formats, a larger one being four times the format used to output alphanumeric characters. Special characters can be located on the screen in a random fashion, the working field of the screen being a matrix comprising 256×256 addressable points. Analogous working field is used to output vectors and circles.

It is possible to display separate points specified by coordinates X and Y with their concatenations. In the latter case, every point in a concatenation is given coordinate Y, while the displacement along X-axis is carried out automatically according to a constant increment value. These modes of operation use the screen working field in

the form of a matrix comprising 1024 × 1024 addressable points. The picture regeneration cycle is equal to 1/16 s, approx.

To store subroutines describing the available set of alphanumeric and special characters, use is made of the storage module of the display processor. The capacity of the storage module usually amounts to 512 words, word format being 24 bits. This module holds data describing about 50 alphameric characters (numbers and Latin alphabet letters) and approximately the same amount of special characters. If necessary, use may be made of an extended set of characters whose description is placed in a special storage module or in that part of the display processor storage which does not hold the data output program. The fashion in which the display processor storage is used is typical of the Ferranti Limited indicators.

Eight instructions accessible to the programmer are used to control the indicator, each of which being placed in the display processor storage in the succession in which data are to be displayed on the CRT screen. For describing the instructions, use is made of octal codes between 170 and 177. Instruction codes are placed in the bits of the words 1-7.

Code 170 describes the selection (switching) instruction used to identify the indicator with which the display processor must work. The indicator number is placed in the bits 13-24, each indicator being assigned the respective bit. When the indicator is operated in conjunction with MD-4, all the above bits are normally zeroed.

Code 171 is used for transfer instruction. The branch address is stored in the last 12 word bits. The bits 8-11 contain the following data:

bit 8 determines branch condition. When the bit represents a 1, this is the end-of-frame bit. If the display processor is actuated to execute a branch instruction during picture display, with a 1 in the bit 8, the electron beam is set at the beginning of the frame and, on the arrival of a regeneration pulse, the entire display program is run again. With a 0 in the bit 8, the instruction which is next in time sequence (stored at the branch address, i.e. in the last 12 bits of the given word) must be executed;

bits 9 and 10 are used to specify the number of the character set to be used during data output. There may be four character sets whose content is determined by the user. After execution of a branch instruction, all the following data will be displayed by using the character set whose code is described by bits 9 and 10;

bit 11 represents a 1 provided italics are to be used during text data output. The letters are displayed in this case at a tilt of 18°, approx.;

bit 12 is used to specify the number of characters per line. With a 1 in the bit 12, one line includes 32 characters, while a 0 in the bit means that 64 characters are contained in a line.

Code 172 describes an instruction to be executed to display a succession of equidistant points. To write the instruction, two successive words in the storage are used. The first word contains the instruction code (bits 1-7), increment in coordinate X (bits 8-9), and also coordinate X of the initial point (bits 17-24). The bits 10-16 of the first word are vacant. In the second word, a 0 is constantly held in bit 1, bit 2 is vacant, and bits 3-12 and 15-24 are used to specify the ordinates of two points displayed in succession.

It is evident that the number of words that follow the first word is determined by the number of pairs of points displayed in succession. The bits 13-14 of every second word are vacant.

Code 173 is given to the point output instruction that deals with points defined by their respective coordinates X and Y. The bits 1-7 are used to hold the instruction code while the remaining bits are kept vacant. To specify the coordinates of each point, use is made of the word which is placed in the storage, following the instruction code word. The coordinate X is placed in bits 3-12, whereas the coordinate Y, in bits 15-24. The bits 2, 13, 14 are vacant. The first bit always contains a 0. The number of words following the instruction word is determined by the addressable points. Since the display processor storage contains 4096 words, it is possible to display simultaneously about 4000 addressable points on the CRT screen.

Code 174 describes an instruction used to display circles. In the instruction word, bit 8 represents the type of the line being displayed. With a 0 placed in the bit, a solid line is specified, while a 1 in the bit means that the line is dotted. To define the coordinates of the circle centre (ordinate and abscissa), use is made of bits 9-16 and 17-24, respectively.

Each word following the instruction word is capable of specifying two values of the diameters of the circles to be displayed, the first value being placed in bits 8-15, and the second, in bits 17-24. The bits 4-7 indicate the number of the quadrant in which the arc length of the corresponding circle has to be displayed. To display a circle, all the above bits should contain a 0. The bits 2-3 and 16 are vacant.

Code 175 describes the instruction used to display short vectors whose length is determined by the relative coordinate values to specify the vector end and the absolute coordinate values to specify the vector beginning. The ordinate and abscissa of the vector beginning are placed respectively in bits 9-16 and 17-24 of the instruction word. Like code 174, bit 8 of the instruction word represents the type of the line being displayed. The second word following the instruction word specifies the relative ordinate (bits 7-15) and abscissa (bits 16-24). The bits 2-6 are vacant. The bit 1 of the second word should always contain a 0.

Code 176 conforms to the instruction used to display special characters. A 0 placed in bit 8 of the instruction word means that the character being displayed flickers; no flicker occurs with a 1 placed in that bit. The coordinates of the character appearing first in a given sequence are placed in bits 9-16 (coordinate Y) and in bits 17-24 (coordinate X). The words describing the codes of the characters being displayed follow the instruction word. There is a particular bit for each character which represents the attribute describing the character format. One word contains the codes and attributes of three characters displayed in succession. The character code is first placed in bits 1-7 and then the format attribute is written.

Code 177 describes the text output instruction. The bit 8 represents the flicker attribute, while bits 9-24 represent the ordinate and abscissa of the text beginning each of which occupies eight bits respectively. Written after the instruction word are the words that contain the codes and format attributes of three text characters in succession. The code and the format attribute of a character require each eight bits.

The storage of a modern display processor is operated in a sequential mode. The words describing both instructions and relevant data (coordinates, character codes, etc.) are selected and handled in the same sequence in which they are placed in the storage unit. Transfer instructions are an exception. Their use makes it possible to obtain the desired arrangement of data on the CRT screen when working with alphameric or special characters.

To provide for economical operation of a CRT display, the display processor must use the word length equal to the length of the words handled by a computer which is operated in conjunction with the display.

Character generators are responsible for the output of alphameric and special characters. They use on a large scale the dot-type microraster method. When using this method the screen area assigned to a character position represents a rectangular matrix comprising addressable points. During the display of the desired character, the electron beam is directed in a line-by-line fashion to scan all the points within the microraster. Using the beam current modulation, the desired set of points is displayed. Use is usually made of a minimum-size microraster comprising 5×7 addressable points, which allows a character to be perceived unambiguously and definitely. To place the beam current modulation program in the permanent storage of the display processor, 35 storage bits are required.

To displace the beam over the microraster, television scanning can be employed. During the display of normal- or enlarged-format characters, the number of the addressable points of the microraster corresponds to the enlarged format mode of operation. When normal format characters are to be displayed, a part of the addressable points

is not used. Character positions of enlarged format can be arranged on the CRT screen in such a manner that no spaces appear therebetween in both lines and rows. In such circumstances, alphameric displays can be used to display certain types of graphic data. Character positions of enlarged format are usually used to display special characters relating, for example, to individual elements of an electric network diagram. Using a suitable set of special characters, one can display an electric network diagram with necessary alphameric letterings. Such character-mode displays are known as *pseudographic*.

The image quality is influenced considerably by the performance of the deflection and focusing systems of CRT. The maximum permissible image drift should not exceed half the diameter of the light spot, which means that it should be commensurable with the CRT resolution.

Many CRT indicators use for character display a raster comprising a fixed set of vector segments whose length, tilt and location within a character position are chosen so as to perceive distinct and unambiguous characters. In the simplest case, the beam scans sequentially the desired set of vector segments; only those segments are displayed which are necessary to delineate the character of interest. The number of bits in which the beam current modulation program is placed is equal to the number of elements included in the given set of the vector segments. As a rule, use is made of sets comprising 24 to 32 vector segments. Thus the described method requires smaller amount of the permanent storage than the dot-type microraster method.

Programmable segment method considerably lowers the character display time. Prior to displaying, each character is approximated in terms of piecewise-linear function. Its contour is divided into a number of segments. Thus with the beam displaced continuously a condition is achieved in which the character is perceived distinctly and can be easily recognized.

The experience shows that five vector segments are required on the average to describe any character in a set comprising numbers and letters of Latin and Russian alphabets. Unlike the above method in which the desired vector segments of a fixed set are displayed, the programmable segment method uses for each character its own program to control the beam movement. As a result, the amount of the permanent storage required is increased.

Vector generators are designed to control the displacement of the beam from a certain point on the screen having coordinates X_0, Y_0 to a given point with coordinates X, Y. Depending on the degree of beam current modulation performed by the brightening unit (Fig. 3.2), the straight line connecting the points may have different shape and brightness. Data are displayed by specifying the coor-

dinates of the end of each vector according to a sequence that determines the forming conditions of the desired picture. This generally ensures adequately illustrative representation of graphic data of any degree of complexity. The image quality of such curves as circle, ellipse and the like depends in this case on the number and length of the vectors used to approximate the shape of the curves. The maximum permissible number of vectors which can be used simultaneously to display the pictures is determined by the capacity of the on-line storage of the display processor, the speed of the beam displacement, and the picture regeneration time.

To automate the curve display process, some CRT indicators use standard display subroutines which are implemented by means of certain character generators. Among them circle and ellipse generators are most frequently encountered. A circle is given parametrically in relative coordinates as follows:

arc length displayed in quadrants I and II

$$\Delta X = X - X_0 = R - \sum_{i=1}^{2R} \delta X_i$$

$$\Delta Y = Y - Y_0 = \frac{R}{\delta Y} \sin \frac{\pi \sum_{i=1}^{2R} \delta X_i}{2R} \tag{3.4a}$$

arc length displayed in quadrants III and IV

$$\Delta X = X - X_0 = \sum_{i=1}^{2R} \delta X_i - R$$

$$\Delta Y = Y - Y_0 = -\frac{R}{\delta Y_i} \sin \frac{\pi \sum_{i=1}^{2R} \delta X_i}{2R} \tag{3.4b}$$

where X and Y are the current values of the beam coordinates on the CRT screen in binary code, X_0 and Y_0 are the coordinates of the circle centre, R is the radius of the displayed circle in binary code, δX and δY are the coordinate increments used in constructing the circle. In most cases, the increments δX and δY correspond to the unit change in the coordinate binary code, i.e. $\delta X = \delta Y = 1$.

To provide for the control of the beam movement, it is necessary to convert digital signals produced by the display processor to analog signals to be applied to the plates of the CRT deflection system. This is performed by means of digital-analog converters (DACs).

One CRT display usually employs several DACs. One pair of DAC's serves to control the main deflection system (MDS) as shown in Fig. 3.2. The inputs of these DACs receive from the vector generator (*VG*) the signals representing the binary codes of the coordi-

nates X_0 and Y_0 that determine the initial position of the beam on the CRT screen. The coordinates X_0 and Y_0 are usually specified as part of the instructions constituting the data output program being carried out by the display processor. Since the absolute values of the coordinates X and Y are generally positive, the DAC's of the MDS are allowed not to use the sign bit, and the address of each point is produced by the display processor in the form of a positive integer number in binary code. The zero values of the coordinates X and Y correspond to the position of the beam at the upper left-hand corner of the screen. When all bits of the registers RX and RY contain 1's, the beam is displaced into the lower right-hand corner of the screen.

Some CRT displays use a coordinate defining system which produces the origin corresponding to the beam position at the screen centre. In this case, the employed DAC must use sign bit.

It is evident that the number of bit positions available to a DAC is determined by the number of addressable points which are set along horizontal (RX) and vertical (RY) lines. In character-mode displays, the MDS is used merely to select the corresponding character position on the screen. The number of character positions in a line and row may be different. Thus the DAC's of the registers RX and RY must contain different number of bit positions.

In graphic displays, the registers RX and RY usually contain the same number of bit positions, since the screen working field forms in most cases a square matrix with addressable points.

The other pair of DACs is used as part of generators producing characters, vectors, etc. It is standard practice to use one pair of DACs for each set including characters of like format and design. When only alphameric characters are generated, each character generator works with one pair of DACs common to all characters. These DACs use timebase amplifiers to control the auxiliary deflection system (ADS) (Fig. 3.2). During the display of a character, the desired beam movement is specified in relative coordinates. This allows for the use of one and the same character generator in order to display a particular character at any character position. Thus the DACs of the ADS usually have their input registers provided sign bit.

Assume that a CRT display shows alphameric characters of a single format. The data are output on 32 lines each of which may contain maximum 64 characters. The characters are produced by generators fitted with a microraster including 5×7 addressable points. Also assume that the MDS is responsible for initial setting of the beam in such a manner that it is directed towards the upper left-hand point of the microraster of each character.

To control the MDS, use is made of two DAC's. The first converter is designed to displace the beam along a horizontal line and has

input register *RX* with six bit positions. The second converter is used to displace the beam along a vertical line and has five-bit input register *RY*. The character generators operate to direct the beam successively over the lines of a microraster and to apply beam current modulation signals to the brightening unit, thereby resulting in the display of the desired points. The ADS DAC is provided with three-bit registers *RX* and *RY*. At the moment when the master oscillator of the display processor produces a first clock pulse, code 000 obtainable from the region of the permanent storage corresponding to the character being displayed is applied to registers *RX* and *RY*. As a result, the beam is set at the first point on the first line of the microraster. Concurrent with this event, a signal from the permanent storage is applied to the brightening unit. The magnitude of this signal depends on the content of the first bit of the modulation code placed in the permanent storage and corresponding to the character being displaced. The code held in the register *RX* becomes equal to 001, while the code in the register *RY* is maintained invariable. After that, the second bit of the beam current modulation code is read out of the permanent storage.

The described procedure is completed after codes 101 and 111 have been placed in registers *RX* and *RY*, respectively. Concurrent with this event, the last (35th) bit of the beam modulation code is read out and transferred to the brightening unit.

The control board (*CB*) of a CRT display unit may be implemented as a separate unit (Fig. 3.3) or may form a part of the indication unit (*IU*), as in the case of VU-2000 display (Sintra Company, France) shown in Fig. 3.4. The control desk of any indicator includes alphameric keyboard (*AK*), see Figs. 3.3 and 3.4. The number of keys in the keyboard is chiefly determined by the set of characters represented by the display. In the simplest case, use is made of the keyboard of a conventional electric typewriter, which can also be used for printing out the displayed data. In addition to the keys providing for character display, the keyboard has another set of control keys used to control the character position on the screen.

The location of a character displayed by means of the AK is indicated by a marker whose movement is controlled by virtue of special keys. Using these keys, the operator is able to move the marker to the right or to the left, upwards or downwards, across a diagonal, etc.

Special aids are used to provide for rapid and convenient movement of the marker. Figures 3.4 and 3.5 show a set of such aids operated in conjunction with the UV-2000 and the Ferranti Limited display unit.

The working element of the *tracking ball* (*TB*) is its upper portion that projects over the panel. By pushing the upper portion, the operator can rotate the ball according to his preference. The angles

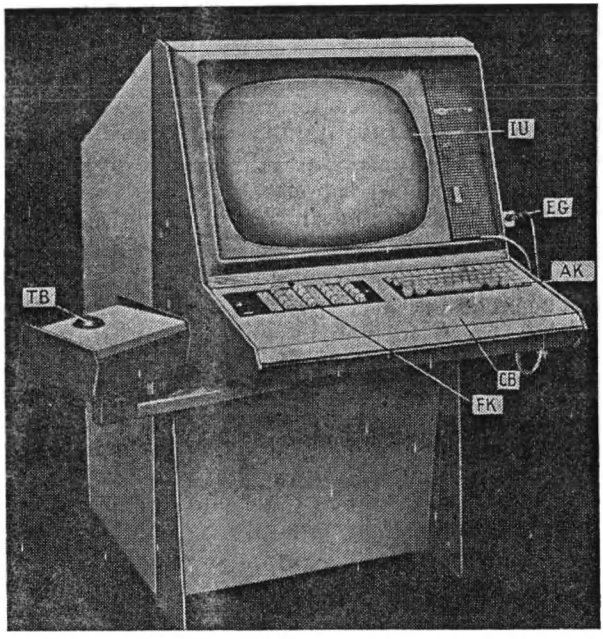


Fig. 3.4

of rotation of the ball about two mutually perpendicular axes in a horizontal plane are sensed by an angle-to-digit converters whose outputs produce binary code signals. The signals are input to the display processor which can handle them to specify the coordinates X and Y of the marker. Using this mode of operation, it is possible to rapidly display on the screen highly illustrative representations of alphameric and graphic data and also to correct and edit the data.

Joystick (*JS*) shown in Fig. 3.5 connects its angle-to-digit converters. The displacements of the joystick in either direction in two mutually perpendicular planes are sensed by the converters and the respective signals are input to the display processor in the form of the marker coordinates. Unlike the tracking ball, the joystick provides both for the control of the marker position and for the setting of the marker speed, which depends on the joystick speed. The tracking ball and the joystick can also be used to control the beam position (drawing mode) and determine the direction in which the entire picture, or a part of it, is to be displaced. A computer is used to control the picture movement. In this mode of operation, the current coordinates of the marker produced by the display processor are input to the computer which works out the difference

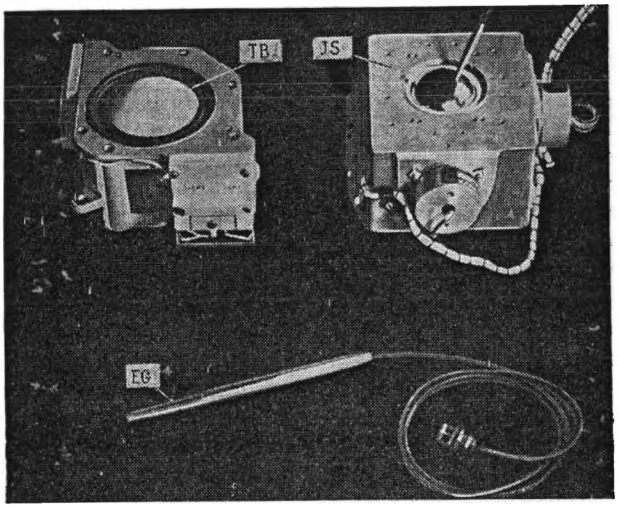


Fig. 3.5

between them and the preceding coordinate values. The values of ΔX and ΔY so obtained are used to determine the desired change in the initial address of the data being displayed.

Electronic pen EG shown in Figs. 3.4 and 3.5 is a device that senses an electron beam impinging on that point of the screen towards which the gun sensitive element is directed. This action results in a change in the capacitance of the sensitive element. There is another device of similar type, i.e. a *light pen*, which senses the luminescence of the phosphor activated by an electron beam. The end face of the light pen usually has a lens whose focus point accommodates a photodiode or fibre-optic light guides that receive the light beam and transmit it to a photomultiplier tube. A phototransistor or a photoresistor may be used instead of a photodiode. The resolution of the described devices is comparatively small, i.e. about 1.5 mm for the light pen, and slightly less for the electronic pen. As compared to the light pen, the electronic pen has a higher reactance because it eliminates data output delays caused by the phosphor persistence.

The electronic pen, and the light pen too, can sense the picture only in the energized state. They are turned on by means of a switch located directly on the device body or on the foot-operated pedal. Though both the devices are operated differently, they are similar from the functional point of view. They can produce an output signal only when an element of the picture being displayed is within their fields of vision. As a rule, that signal is conveyed

concurrently to both the computer and the display processor. In the latter, the appearance of the signal interrupts the picture forming program, while the computer, when influenced by signal, stops executing the current program. According to the interrupt, the computer investigates the quiescent state of the display processor and determines the address and coordinates of the picture element sensed by the pen. After that, the picture element can be handled as desired: for example, the given character is replaced by another one or is transferred to another location, etc. This is done in accordance with the operator's direction or through the use of a particular program.

Either of the above devices can be used to draw the desired picture on the screen. The drawing mode is usually implemented by a program utilizing an accompanying symbol. After the coordinates and program address of the picture element sensed by the device have been determined, the accompanying symbol is displayed at the specified location and the program to govern the following movement of the device is initiated. Each new position of the device is searched for in a cyclic manner and the points or vectors are displayed over the path traversed by the device.

Functional keyboard (*FK*) shown in Fig. 3.4 is a part of the indicator control desk used to control the steps involved in data processing and display. Pressing of functional key produces a request in the display processor according to which it communicates with the central processing unit of the computer. A particular request code corresponds to each functional key.

In accordance with the accepted method of handling requests input to the computer from external devices, an interrupt occurs in the central processing unit. This event causes the computer to execute a subroutine associated with the request code received. Thus the mix and content of the operations performed by means of the functional keyboard is determined by the number of its keys and the set of previously compiled subroutines held in the computer storage. The functional keyboard usually performs such operations as sequential change of frames, shift and change of picture scale, etc.

The assignment of a particular functional key can be modified by changing its subroutine. Thus the keys usually have no permanent letterings and their functions are described on changeable service data plates. In some cases, the keys are provided with computer-controlled illumination aids. This allows the operator to check the procedure in which a given request is handled and, sometimes, to determine the sequence of operational steps, thereby avoiding erroneous actuation of the keys.

Interface unit provides for the transfer of data between the computer, display processor and the additional data input-output

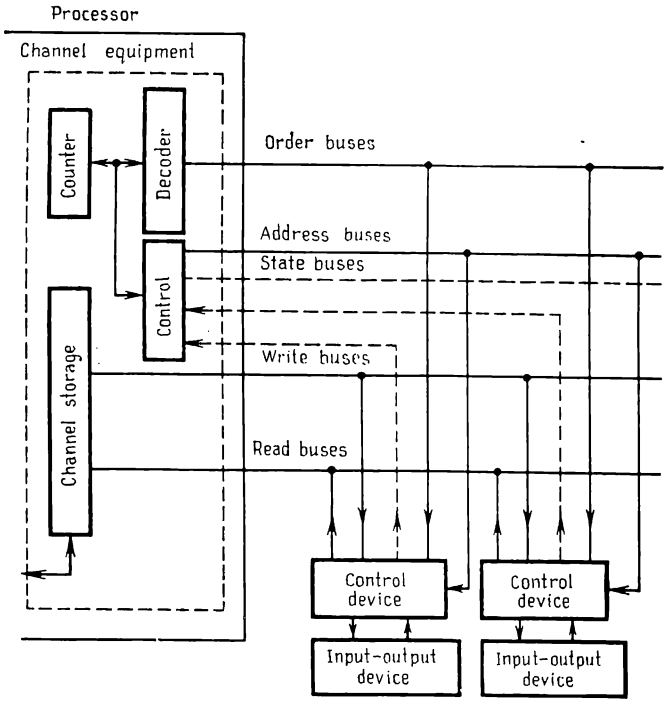


Fig. 3.6

and logging devices, which may be connected to a CRT display unit. If the CRT display unit, computer and additional devices use different design components, the interface unit ensures their easy compatibility.

With a short distance between a CRT display unit and a computer, the latter is provided with a standard-type communications multiplex channel. A connection diagram (Fig. 3.6) to connect CRT display units to the multiplex channel is identical with that used for connecting any other input-output devices to respective control devices. The control device of each input-output device is coupled to the buses of the multiplex channel, which has a storage, an order counter, an order decoder and a control facility to control the address and the state buses. The channel equipment is coupled to the control devices via a set of buses (Fig. 3.6), which provide for the transfer of data between them and the computer in accordance with the accepted procedure of servicing the requests produced by the input-output devices. The channel is operated to apply to the address buses the address codes of the input-output devices; assess the input-

output device state acknowledgement signals transmitted through the state buses; produce orders passed through the order buses; write input data and read output data using write-read buses.

When the distance between the computer and CRT display unit is long, the transfer of data between them and the computer is effected through telephone channels. In this case, the validity of data exchange is usually increased through the use of data transmission systems (DTSs).

3.3. Data Display Systems at Control Centres

The control centres use the conventional means of display, i.e. wall diagrams and control desks for the control engineers.

Wall Diagram. It depicts the entire grid system as a complete network by using standard-type designations of generators, transformers, switches, etc. The desired details to be indicated are selected depending on the importance of a given installation to the entire grid operation. Thus, certain very essential installations (electric stations and substations) are displayed on the wall diagram with a higher degree of particularization. The equipment voltage ratings are shown in different colors. In the Soviet Union, the control centres use mosaic wall diagrams consisting of standard-design sections. The writing surface of each section comprises square elements of standard size (4 × 4 cm). Inscribed on each element are different picture patterns such as line segments, letters, digits, special symbols, their fragments, etc. After new transmission lines, stations or substations have been commissioned, relevant information is introduced by changing the respective elements of the mosaic pattern. The size of a particular character or symbol is so selected that the control engineer can discern it unambiguously when viewing from its work place. Thus the size of the working surface of the wall diagram is determined by the number and details of the items of the network being displayed and also by the desired dimensions of the employed characters, symbols and other picture elements.

In addition to network representation, the wall diagram shows the current state of switching equipment, the information being transmitted by means of telecontrol devices in the form of telecontrol signals (TSs). Depending on the degree of particularization of the item being displayed, the outputted indications may concern either telecontrol signals relating to individual switches or the final state of a set of switches. In the latter case, logic decoders receive telecontrol signals from all the switches in the set in order to determine its final state. A logic decoder will be an OR gate when a transmission line connects the substation buses through two switches, this connection being represented on the wall diagram by a generalized symbol.

The switch positions are displayed by telemeter indicators. The working surface of a telemeter indicator is a glass screen whose interior receives a beam of light from two lamps. A transparent tinted mask is installed between each lamp and the screen, the masks of red and green tints being used. The indicator screen is inserted in a mount whose dimensions are equal to those of a standard mosaic element. Thus a telemeter indicator can be mounted at any location of the wall diagram.

Depending on the magnitude of a telecontrol signal transmitted by a telecontrol device, the respective lamp lights up to project green alarm (turned on) or red alarm (turned off) on to the indicator screen. To allow the control engineer to identify the event of changing a telecontrol signal, the lamps are switched over merely in accordance with an acknowledgement signal. If the telemeter indicator gives an erroneous indication of the current state of the switch, it is transferred to a flash light mode. To correct the erroneous indication, use is made of an acknowledgement panel on the control desk.

The wall diagram can also have recorders and digital indicators to represent telemetered data (TD) on the power flows through network branches, voltages existing on network nodes, total generation of electric stations, etc.

There is a particular group of wall diagram indicators, digital or analog, which is used to indicate astronomical time, frequency, frequency derivative, difference between electronic clock and astronomical times, etc. In some cases, wall diagram digital indicators are used to display data on power system total loads and generation, net power interchange, etc.

Used as indication units of digital displays are gas-filled signal lamps and matrices comprising 5×7 or 7×10 incandescent lamps. The size, luminance and contrast of indicating means of digital displays must provide for a high recognition rate and unambiguous perception of each character as viewed from the control engineer's work place.

The wall diagrams with telemeter indicators use as a rule non-illuminated mimic symbols (the so-called dark wall diagrams). The size of a wall diagram is determined by the number of mimic diagrams (the dimensionality of the pattern being displayed).

The wall diagram area factor refers to the ratio of the area occupied by mimic elements, letterings, instruments and indicators to the wall diagram total area. It should not be more than 0.4 with allowance made for the growth of conventional power systems.

The lay-out of mimic elements on a wall diagram should meet the following requirements:

the wall diagram shows merely those objects which are under direct or co-ordinate control of the given control centre;

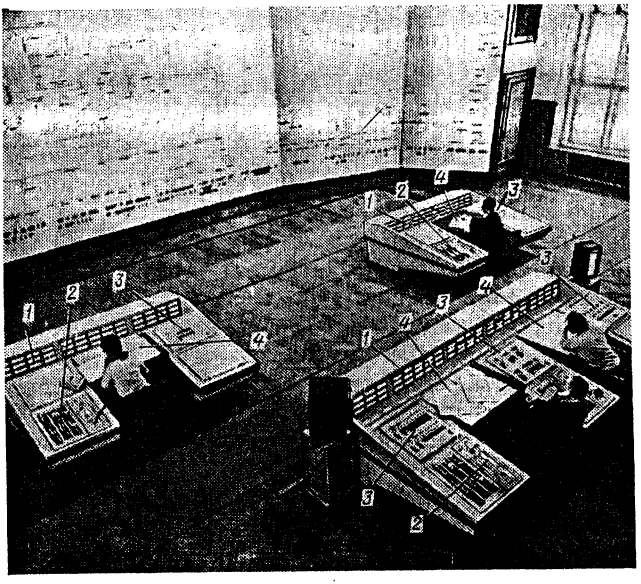


Fig. 3.7

the angle of view of the frontal plane of the wall diagram must be within 40-60°;

mimic elements depicting high-tension transmission lines should be as short as possible, the number of their intersections should be minimum; also, they should not be located close to each another;

mimic elements should be shown in colors whose contrast differs from that of the color of the diagram surface; it is good practice to use direct-contrast mimic elements, i.e. dark lines viewed against light background;

the display colors should be chosen in number not exceeding seven;

the size of mimic symbols should meet the requirements of optimum discernibility. This means that the optimum size of a mimic symbol must correspond to an angle of vision of 30-40′, and the minimum size, to an angle of vision of 12′;

the angular size of mimic pictures showing individual power installations on the wall diagram should not exceed 18°, which is the limit angular size of the zone of instantaneous vision.

Control Desks. The control desks are designed on the basis of source data that could satisfy the conditions of convenient and efficacious control to be exercised over all technical facilities of operational information-oriented system of the automated dispatch

control system, including computation facilities, data display devices, communications and telecontrol channels, and automatic schemes controlling system frequency, real power flows and other variables. It is important to stress that data displayed by the wall diagram, instruments and other indicators contained in the control room must be positively discerned and rapidly recognized by the control engineer at his work place.

In the Soviet Union, the control centres use one-, two- and three-position control desks, which are a part of the delivery set including mosaic wall diagrams.

A control desk (Fig. 3.7) basically consists of the following: instrumentation panel *1*; control panel *2* to control communication channels and control engineer's tape recorders; panel *3* to control wall diagram equipment and ALFC schemes; writing surface *4*. The right- and left-hand sides of the control engineer's work place mount the control panels. The instrumentation panel and the writing surface face the control engineer's work place.

The working surface of the instrumentation panel can accommodate specialized analog devices or digital indicators of equal size, which are connected to telecontrol devices. A small tilt of the instrumentation panel allows the control engineer to rapidly and accurately take the readings off each instrument while viewing from its work place. The design and location of the controls meet modern human engineering requirements.

The described control desks have no CRT display units. At the present time, design work on control desks aims at constructing devices that would utilize CRT display units compatible with computers.

Equipment Installed at Control Centres. A major device used to display and control data handled by the ADCS is a CRT display unit which is operated in conjunction with fast printers and graph plotters capable of outputting data in the form of hard copies. Important to these operations is the display functional keyboard which can provide for considerable simplification and automation of retrieval and editing of data.

The experience gained both in the Soviet Union and abroad shows that CRT display units and other modern data output means can be used along with conventional equipment such as wall diagrams. In Britain, for example, the National Dispatch Centre equipped with CRT display units and many advanced data output and register devices uses a wall diagram with digital and analog devices (Fig. 3.8). Two-position control desks are fitted each with four CRT display units manufactured by Ferranti Limited (see Sec. 3.2). To control the displays, the control engineer's work place is provided with functional keyboard having tracking ball. This allows for rapid and convenient search, editing and display of data. Thus critical opera-

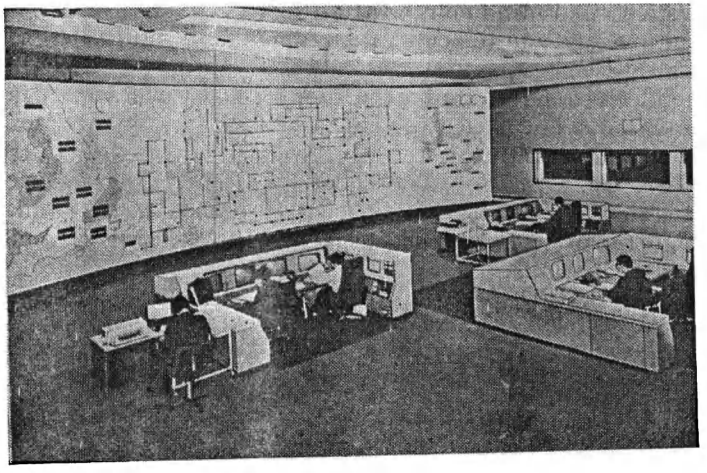


Fig. 3.8

tional tasks are tackled, which are concerned with system reliability and maintaining current and predicted operating conditions in the most economical manner.

Figure 3.9 illustrates a control desk manufactured in the Soviet Union. The desk uses CRT display units as major data output devices. A mosaic wall diagram with telemeter indicators and digital devices is used to increase information capacity of such control desks and to provide standby facilities.

Figure 3.10 shows the interior of the control centre of the USSR United Power Grid Central Control Board. Telemeter indicators and digital devices of the wall diagram depict a major electric network of the grid and show its current state variables. At the upper part of the wall diagram, four digital devices of enlarged size show the following data: system frequency; system frequency derivative with respect to time; astronomical time; grid total generation. A three-position control desk is equipped with the following: panel with analog and digital devices; wall diagram control panel; panel to control communications channels and control engineer's tape recorders; control panel for CRT display unit.

The proper choice of the design features of a control desk should take into account the operational capabilities of the entire complex of the ADCS technical facilities. The following characteristics are critical in designing the ADCS data representation system:

the control room: dimensions, space orientation and remoteness with respect to computation, communications and telecontrol facilities;

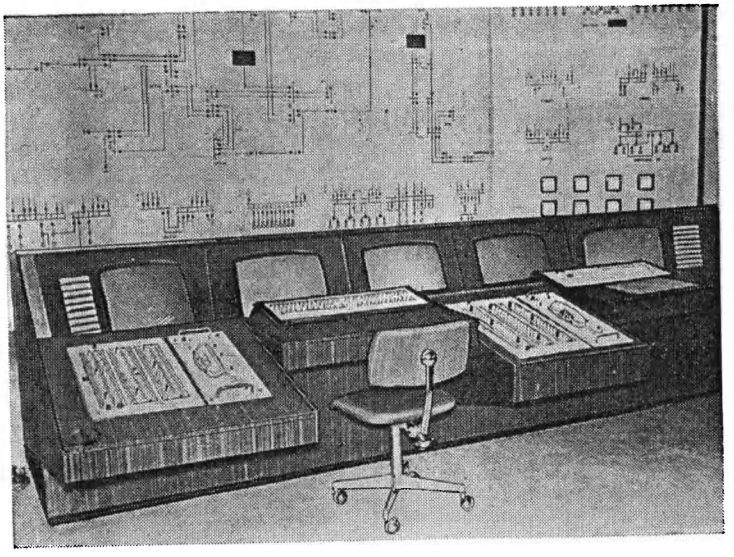


Fig. 3.9

expected working parameters, including amount of all types of data and the speed and periodicity of inputting thereof;

maximum permissible delay time between the points at which each type of data is inputted and displayed;

the characteristics of each data output device as stated in Sec. 3.1;

program-oriented and operational characteristics of computation facilities;

characteristics of communications channels, telecontrol devices and data transmission systems.

Since all the factors listed above should be dealt with on an integrated basis, the problem of proper choice of technical facilities of a control centre is considered to be comparatively complex and solution to it can be achieved by using system analysis methods.

The components, dimensionality and periodicity of solving the tasks concerned and, consequently, the amount, speed and periodicity of data inputting depend on the accepted organizational features of dispatch control, network configuration, the number of power installations and their characteristics, and on the mix, siting and operating conditions of users' installations.

The equipment installed at control centres must be an integral part of a real-time computer system, RTCS (see para. 2.8 of Ch. 2). This means that all control centres must be equipped with those dispatch and production process control facilities which can provide, when operated in conjunction with the RTCS, for tackling all tasks

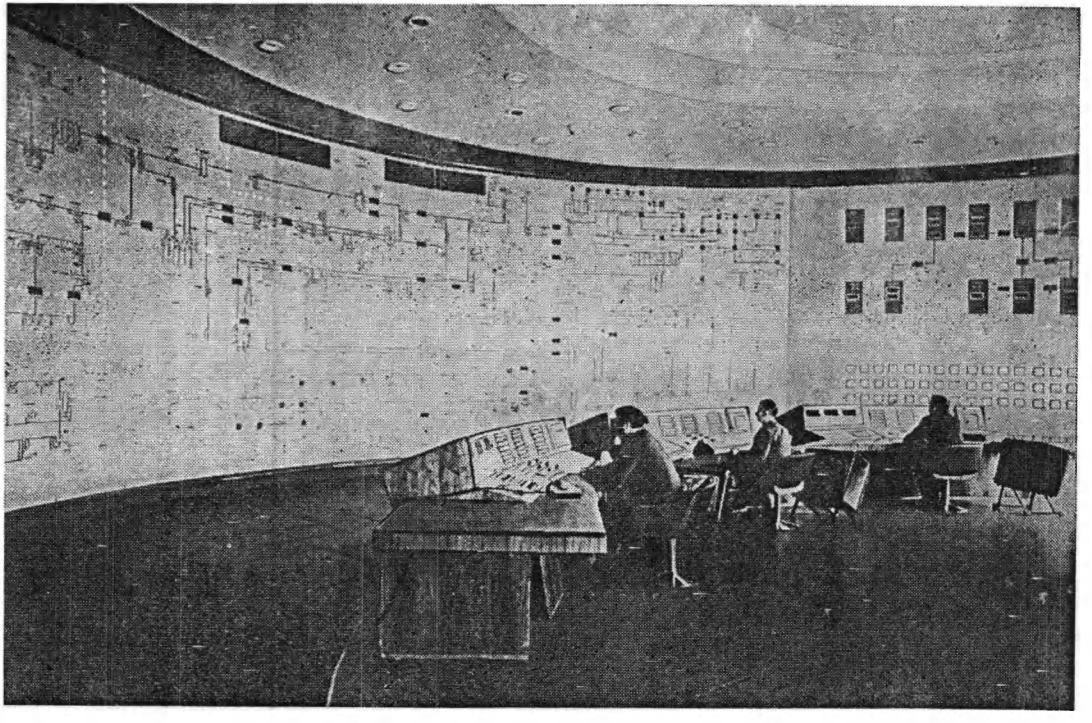


Fig. 3.10

involved in real-time dispatch control activities to be performed at the given level of the command hierarchy.

The control centres and dispatch and production process control stations (DPCSs) should take mains line power from two independent a.c. power leads. Emergency power supply can be taken from accumulators or automated diesel-generator sets. Those devices which must be fed on an absolutely continuous basis require the use of accumulators as emergency power supply, but devices that allow for short-term interruptions in power supply are fed in this case from diesel-generator sets or inverters.

To obtain better work in control rooms, control centres should be equipped with ventilation and air conditioning systems whose proper choice depends on climatic conditions and characteristics of computing, communication and telecontrol devices employed.

REVIEW QUESTIONS

1. Describe the relationship between resolution and information capacity of a data display device.
2. How would you assess image contrast?
3. What is the relationship between image color and luminance?
4. What is the preferable way of determining minimum discernible dimensions of a character?
5. Describe the parameters that determine information capacity of a CRT display unit.
6. Describe the parameters that determine regeneration rate of a picture on a CRT screen.
7. What are major functions of a display processor?
8. Describe the principal methods of generating characters as applied to CRT display units.
9. What are the principles of operation of light pen and the functions of electronic pen?
10. What are the principles of operation and functions of tracking ball and joystick?
11. Describe the purpose and principle of operation of functional keyboard.
12. State the factors which should be taken into account in designing data representation system of control centre.

Chapter 4

Computers in Power System Control

4.1. General

The power industry control means and methods are developing through creation of centralized systems utilizing computers of various types (digital, analog, hybrid). The created systems have proved the advantages of the new approach over the previous trends wherein isolated limited-function devices were correlated to the notion of "system" only within the framework of the general control process without any allowance for their structure or implementation.

The electric power industry is one of the branches which promotes the modern means and methods of data processing, digital computers among them. It suffices to say that, e.g. one of the USSR-first digital computers, the МЭСМ type computer developed in the Ukrain in 1955-1956, was intended for computing the conditions of electric power transfer from Kuibyshev to Moscow. The electric power industry is one of the largest consumers of large scientific computers. Similarly to other branches, the power industry utilizes computers for managing the economic activities of enterprises at all hierarchic levels. Process computers are used at enterprises (electric power stations, substations) for controlling technological processes. Besides, the power industry has a particular field as if incorporating both of the control systems considered above—the automated dispatch control systems (*ADCS*).

The ADCS usually comprises the facilities of two kinds: the off-line systems forming regular computing centers (often with data teleprocessing) and real-time systems utilized directly by the dispatching personnel of the power systems and networks. Let us consider the main tasks of said systems and ways to achieve them with reference to power industry planning and control features in different countries.

Power industry is one of the vital branches of national economy in any country. It dictates the life of vast regions and sometimes of the entire country. Therefore, in some capitalist countries, such

as Great Britain and France, the power industry is nationalized. These countries also have positive dispatch systems with stringent regulations. The dispatch systems usually have three levels. The highest level in the USSR dispatch system is the Central Control Department of the United Power Grid (*UPG CCD*); the medium level includes power areas subordinate to the Area Control Boards (*ACB*) and power regions supervised by the dispatching services of regional offices and served by the regional control boards (*RCB*); the lowest level are the personnel of the stations and substations, as well as the dispatching bodies in distribution networks.

In case of large objects being of vital importance for several power systems and zones, the hierarchy of dispatching is violated. Such objects (large thermal and hydroelectric stations, large node substations with trunk lines), though belonging to regional power administration, are supervised by the dispatching bodies of higher hierarchic levels.

Introduction of a three-level dispatch system is completed in Britain and France; this proved to be practical even when the RCB is in the same building with the area dispatching center. There are 6 or 7 second-level dispatch areas in these countries.

A different situation is found in the USA where separate power generating companies are essentially private firms and joint stock bodies. These companies are called "utilities" and supply energy to towns, regions and sometimes to the states. A particular feature of such companies resides in a wide diversity of scale, potentials, structure and organization of control. Some of them own power stations and networks and serve vast areas. The other (which are few in number) do not have their own stations (or may have some) and only distribute energy purchased from the neighbors.

Inasmuch as the networks of all the utilities are interconnected all over the country (but for Texas), the complexity of operation of such a system and the part played therein by the devices for controlling power exchange between separate areas become obvious. If an area served by one group of devices includes several separate utilities, it is called "pool". The pool participants may operate at free transfers of power. The power revenue metering is effected by a special team supervizing operation of the pool. The dispatching functions are among the responsibilities of such teams.

At present many pools are merged into superpools where respective management teams are also formed. Another step has been recently taken in this direction. To coordinate efforts in increasing reliability of parallel operation, the Federal Power Commission of the USA has divided the country into nine zones where the respective utilities have established special bodies intended to plan joint operation of said utilities, including those integrated in pools and superpools. Thus, the hierarchic power industry control system

is also found in the USA where vast experience in the use of computers have been gained.

The first function of the dispatching bodies at all levels is to forecast the load and plan operation of the power systems, effected in stages starting with short-term (day) planning and terminating in long-term planning with a view to controlling the development of the power systems. Each stage involves various tasks: economic, technoeconomic and purely engineering ones (e.g. stability studies calculations, short-circuit currents, etc.). All these tasks are most frequently solved without relation to the real-time control process. At the conventional computing centers such facilities usually serve the dispatching offices, as well as support, design and research organizations. Preference is given to the dispatching problems though the time spent for them is comparatively insignificant (about 20% of the total).

Another function of the dispatching bodies are operative supervision and correction of conditions, elimination of emergencies, etc. When executing this function, use is often made of separate units based on small control digital computers or minicomputers. Such complexes are peculiar in their integration with telecontrol and communication means as well as with displays such as synoptic panels and cathode ray tubes. On some occasions these complexes effect direct digital control of load-frequency in the power systems; sometimes, they control switching operations known as "automatic generation control".

The complexes of such facilities are referred to as computing complexes (*CC*) and real-time computer systems (*RTCS*). If they include different facilities, their interconnection is not always necessary: the experience has proved that such an interconnection requires intricate software and preliminary analysis of data transmitted from the RTCS to CC. At the same time, these complexes often have a great plurality of input/output devices each. The CC terminals are provided at lower levels of dispatching systems and allow the respective personnel to get access to large computers. The RTCS terminals installed at the power stations and substations are devices for establishing communication with the personnel of the stations and substations and for direct digital control of said objects. On some occasions such terminals are digital computers provided at the power stations and substations for controlling and monitoring their equipment.

4.2. Computing Centres of Power Dispatching Offices

As outlined in the previous section some functions of dispatch control (analysis, forecast and planning) are performed with the use of facilities concentrated at the computing centers (*CC*). On

some occasions the CC are autonomous bodies. For instance, in the USSR in the early 1970s all the dispatching bodies of two highest hierarchic levels had their own CC provided with one or two computers of the EC-1030 type (speed —63 000 operations per second, storage capacity—256K bytes*, three magnetic disc storage devices with a capacity of 7.25M bytes** each, four magnetic tape storage devices). Some centers are provided with the M-4030 machines (speed of action of about 100 000 operations per second). Now larger computers of the EC-1033 and EC-1045 type are also used.

The complex flow distribution computations are usually performed for a network consisting of 300-400 nodes and 500-600 branches. Optimal generation scheduling is done for a system containing about 50-70 generating nodes, 30-50 load nodes and 20-30 controlled power transmission lines. Stability computations are usually accomplished for a system consisting of 100 nodes and 200 branches (on the assumption that emf remains constant after transient reactivity of generators).

With the above speed and capacity characteristics of digital computers, the autonomous CC of the dispatching bodies are economically feasible. However, the growth in computer capability is accompanied by the price growth and autonomous CC become ineffective since the dispatching bodies cannot ensure economically justified loading of the digital computers. Therefore high-speed computers within the framework of the power administration bodies should be used jointly with dispatching offices, research and support organizations.

Characteristics of some computing centers. The National Control Centre of Electricité de France (EdeF) actively uses the complex of facilities located at the Scientific and Research Center in the suburb of Paris and connected with the EdeF building by a link adapted to transmit data at a speed of 9600 bauds. This complex aimed primarily at solving scientific and research problems has hardware by the CDC company of the USA. The complex is based at present on the CDC-6600 computer, relating, according to the today's classification to the giant machines. To increase the efficiency the CDC-6600 computer is based on the principle of parallel utilization of devices performing groups of operations. In particular, there are four devices for handling floating point operations: an adder, two multiplexers adapted to multiply two 60-bit operands in 1 μs, and one division unit. Besides, there are four devices for performing operations of other types and two machine arithmetic devices.

The capacity of the computer main memory is about 950K bytes at a cycle time of about 1 μs. The memory is time-shared so

* 1 byte is equal to eight bits, 1K byte, to 2^{10} bytes.
** 1M byte is 2^{100} bytes.

that the minimum waiting time is 0.1 μs. Besides, there is instantaneous register memory for storing operands, addresses and codes parallel to accomplishment of operations; the capacity of said memory is 156 bytes. The machine speed is 1.5 million operations per second with 60-digit words.

To increase reliability, the computer is duplicated by another machine (CDC-6400) having approximately three times as low speed. These both computers cooperate with a great plurality of peripheral devices chosen according to the problems to be solved and containing four external magnetic disc memory systems (*MDS*), 21M bytes in capacity each, 12 magnetic tape storage devices, five high-speed printers, one output punch and three regular punched card readers. The complex additionally includes the CDC-3500 computer used to supervise computations and establish communication with terminals, and the CDC-1700 minicomputer for communicating with the economic department computing complex which has the high-capacity UNIVAC-1108 computer. The same machine controls a special color-image projection device with a screen representing the network pattern and distribution of power and voltages along it.

The Scientific and Research Center of EdeF also has an IBM analog-digital (hybrid) unit consisting of the PACE-231 and EAI-9400 machines. It includes over 500 operational amplifiers, 450 servo-set coefficient attenuators, 90 multipliers, 20 function generators, 92 analog storage devices and a 256 four-bit word parallel logic discrete memory. This system, similarly to a smaller system based on the EAI-8900 hardware (285 amplifiers, 100 multipliers, EAI-8400 computer) is intensively used for investigating the power industry control and dispatching means (the small computer system with a physical model of the power system is a digital analog-physical complex).

The CDC machine terminals installed in the EdeF building have a central processor, a 4K 12-bit word memory, a teleprinter, an alphanumeric printer and a punched card reader. The system has been successfully operated for several years which proves the correctness of its principal solutions.

The CC of the Central Electricity Generating Board (CEGB) of England and Wales is somewhat different in its organization. The main equipment is arranged directly in the Administration building in London, and only terminals are located in other towns.

The CC system is based on the IBM hardware which is a two-processor third-generation computing complex; the complex is periodically replaced with higher capacity complexes having higher speeds (1.5-2 times).

During the last replacement the IBM-360/50/85 system was substituted with the IBM-370 system having the main processor of the 370-165 I type (storage capacity of 1024K bytes) and the auxiliary

processor (dispatching computer) of the IBM-155 I type. The main processor includes an instantaneous memory with 4-K byte registers; the speed of such a system is estimated at 2.0-2.5 million operations per second. Besides, provision is made for high capacity of mass memory —improved disc memory MDS capable of storing up to 1600M bytes simultaneously, improved tape memory MTS capable of storing up to 38M bytes on the spool at a transmission speed of 120 K bytes/s, etc.

Contrary to the CDC machines, the IBM-360 and IBM-370 computing systems prove especially effective at joint solution of engineering and economic problems. Among many problems solved by the above-considered system per day, only few are the economic problems, sufficient however to load the system devices not loaded at solution of engineering problems, which is ensured by the flexibility of the operational system in use.

A wide-scale utilization of teleprocessing methods with locating terminals at a great number of allied enterprises has tremendously contributed to increasing the efficiency of the equipment under consideration and further computerization of the British power industry. The first nine terminals of the systems were arranged at the following places: at the National Control Center in London, area dispatching centers in seven towns of England and Wales (the maximum distance to London is 250 km) and at the Central Electrical and Research Laboratory in Leatherhead. The experience gave a good account of itself and the number of terminals connected to the system is fairly high today, the major part of the terminals being arranged in commercial organizations supervising operation of distributing networks rated at 154 kV and less.

The majority of the terminals of the system is based on the IBM-1130 processors regarded previously as independent units. Now they are introduced into the general hardware of the IBM-360 and IBM-370 systems for use at distant terminals. Two types of subscriber's posts with such processors are being utilized at present: the first type includes a teleprinter and an alphanumerical printer, it has a memory of 8K bytes, a transmission rate of 2000 bauds (bit/s); the second type has a memory of 16K bytes and an additional equipment—MDS for 1M byte and punched card input; the transmission rate is 4800 bauds. Some terminals include graphplotters. Besides, the terminals may comprise simpler devices of the 2740 type: a typewriter, a tape punch, and a punched tape input device, i.e. standard teleprinter equipment.

Teleprocessing systems. A great number of intensively used terminals in the CEGB computing system ensured economic feasibility of creating a special teleprocessing system. The system is supervised by a duty operator but most of the functions are automatically

executed by the dispatching computer (i.e. the second computer of the complex).

All the functions for controlling teleprocessing may be divided into two main fields—organization of control over the computing process per se and monitoring of the communication channels.

The first function is usually ensured by the software, while the second, by the hardware. A peculiar feature of this system dictated by the presence of the dispatching computer therein is the possibility of transfer to software the execution of the second function that would allow for using simpler equipment with improving the quality of control. In particular, the data transmission equipment does not have a usual error protection since the respective logic check operations are conducted in the course of processing of the information received. Besides, the operator can use special commands to connect the system to a particular terminal, transmit a message, perform a diagnostic test, etc.

The stringent requirements for reliability of the teleprocessing control system impose a vital importance upon the possibility of checking and logging errors in the communication lines. For instance, if a message failed to pass through the communication channel, the system repeats it automatically. If the desired information is transmitted after several attempts, the operator is not informed of the errors, but they are registered automatically. In case of failure of one of the channels, the operator receives the error statistics. The statistics are sampled in different time intervals—before the first interrogation, before the second interrogation, etc. Thus, objective data on channel functioning are gathered to be further taken into account.

The data processing control by the commands from the terminals is carried out by special control programs responding to addressing from the terminals with the aid of a special language. The set of programs and control language of teleprocessing were introduced in this system for the first time and were developed with immediate participation of CEGB personnel (users).

The IBM company has an improved version of the equipment today but the CEGB still uses the first version which enables a user of any terminal to set up his own file, edit it, direct for processing or storage, or even close the file and start the conversational mode. In each case the terminal user gets access to all the means of the system needed for solving a problem, including program modules stored in the system library. The program modules for solving a plurality of power industry problems appear to be similar irrespective of the organization that uses them. This means that the terminal user may perform the required computations at a fraction of the cost (about 0.1-1.0%) of leasing the entire system. In this case only extra pay for communication channels should be

taken into account (in England, about 0.2-0.3% of the entire system lease cost per channel).

Software. Considered to be the first and main program prepared for dispatch control at this CC is the above-mentioned teleprocessing program which enables the area computing centres (ACC) to take part in elaboration of the national generation schedule. This is effected by inserting data on generation sources ready for use immediately from the ACC, after which the data are automatically introduced into the generation schedule elaboration problem the moment it is solved by the system.

A structure and composition of programs are explained in Table 4.1 which indicates the subunits of the Central Office entitled to order a program. It should be taken into account that some programs (usually marked by "*") are used in the operational computing complex. Many of the programs listed in the table are essentially well-organized program batches or components of such batches.

Table 4.1 is characteristic of a computing center serving a large

Table 4.1

National control center	Operations department	Planning department
*Calculation of power flow distribution (DC model, 300 nodes, 500 lines)	Calculation of power flow distribution (DC model, 600 nodes, 1000 lines)	Calculation of power flow distribution, (DC model, 600 nodes, 1000 lines)
Calculation of complex flow distribution (AC model)	Processing of statistics and forecast of loads	Calculation of complex flow distrtibution (AC model)
Short-term correction of generation schedule in view of data from ACC	Long-term estimation of 24-h generation schedules in view of 550-node network and 1000 constraints	Transient stability studies in view of speed governors and voltage regulators
*Calculation of balanced short circuit currents	Planning of equipment stoppages	Calculation of unbalanced short circuit currents

power interconnection. The table may be complemented depending on the structure of the power interconnection. For instance, in case of dispatching centers supervising a great number of hydroelectric power stations, particular attention is usually paid to the available capacity of water reservoirs and operation of the HPS cascades is optimized. Therefore, their CC have, as a rule, appropriate programs. For interconnections with long-distance super-high voltage transmission lines,

overvoltage calculations are needed, etc. Nevertheless the core of the CC software is made of the programs indicated in the table.

A characteristic feature which transpires from Table 4.1 is the presence of a number of similar programs. These programs are allocated among different subunits where calculations require programs which differ in the data insertion method, formalizing of the results, and, sometimes in the calculation procedure. This is attributed to the fact that final decisions in the solution of the control problems are taken by the man who selects the program modules most suitable for a given problem. It should be borne in mind that modern computing systems are adapted to store different modules and even programs and quickly establish links between them.

An indispensable condition for any dispatching office computing center is the presence of a data file used as an information base for solving problems. The computing center being considered includes, in addition to the load statistics and other data on consumers, the National Catalogue containing all the parameters needed for calculations. The possibility of automatic fetching and utilization of file data for solving the problem without participation of the operator or programmer is one of the most vital conditions for successful functioning of such a system. All the engineering problems solved by the CEGB maintenance subunits at the CC amount to about 30% of its capacity. The research problems and design problems occupy 30% each. The economic problems get about 10% and are solved both by the above-mentioned large computing system and by low and medium capacity machines.

4.3. Real-Time Computer Systems

Meant by the real-time computer system (RTCS) is a set of hardware and software intended for immediate serving of the dispatch centers (*DC*) of power systems and grids. The RTCS differs radically from the CC complexes as being a profound man-machine system operating on a real-time basis. This allows for not only improving operation properties of the DC equipment but also for cutting its operation costs.

Development of RTCS. Creation of real-time computer complexes of the dispatch centers was begun in 20-30's when special centers for supervisory control were established. The principal control means at the initial stage was telephone communication which retains its significance as a dispatching control facility. The wall-mounted (mimic) boards representing the synoptic diagram of the system being supervised appeared at the dispatching centers alongside with the telephones. The purpose of such boards is to remind the dispatcher of a nature of links between separate elements of the system.

Originally, such diagrams showed only the configuration of certain switching equipment in the system without showing the current state thereof. Therefore, they were called "static". The development of supervisory indication made it possible to "animate" the boards with signals showing the current state of the switching equipment and the "animated wall diagrams" term appeared. The experience gained revealed the need for manual control of the boards to represent the state of the objects without remote signalling and correct faulty telesignals. Besides, it was found expedient to receipt the arriving signals (i.e. to acknowledge the reception by the operator). This necessitated the use of special switches and relays the number of which reaches several hundreds or even thousands to-day. Thus, originally elementary mimic diagrams have transformed into a bulky and sophisticated structure the creation and operation of which require considerable expenses.

The next step made towards development of the wall diagrams is linked with wide spreading of control methods. Digital indicators of loads of power lines and voltages across buses were mounted on the board. If such indicators were located near devices that symbolyzed the respective buses and lines, it would be possible to represent the current state of the entire system on the board. This would contribute greatly to improvement of quality and facilitation of labour conditions of the dispatcher but cannot be achieved by conventional means because of a number of reasons (remoteness of the board from the dispatcher's console, difference between day and night illumination, etc.). Separate successful attempts of using special equipment of such a type have not yet found wide application. Therefore, for several decades the meters of the telecontrol system were mounted either on a special function board or on a dispatcher's console, the latter version being regarded as most convenient by many experts.

In addition to mimic diagrams and instruments, dispatcher's job requires sometimes additional detailed diagrams of plants, different instructions and tables. Keeping such materials in regular folders is inconvenient, therefore attempts have been made, unsuccessful up to now, to use special projector with quick search of the required picture.

The experience of running DCs at different hierarchic levels revealed that the console instruments were sufficiently descriptive and convenient at a limited volume of telemetry information, however as the volume increased, which especially manifested at highes level dispatching centers, the situation might worsen drastically Besides, the consoles stuffed with instruments became too intricate and new trends for modifying them had to be found. The CRT displays—an ideal combination of a mimic diagram, function board and projector, have given a good solution to the problem.

The difficulties in this respect are linked with appearance of two expensive display means (boards and CRT) and with the use of space capacity of display control computers. This resulted in proposals for complete discarding of the CRT boards from the dispatch centers and substitution of the boards with a set of color CRT arranged in two horizontal rows (such an attempt was made by one US utility). However, a complex structure suspended from the dispatch room ceiling and provided with a special lifting mechanism for replacement of tubes has not found wide application. The displays of modern DC's are usually arranged near the board.

The utilization of spare capacity of computers is inherent in such installations, since it is difficult to select a computer the entire capacity of which might be feasibly spent for display control. At the same time, the MTTR (mean time to repair) amounts usually to several hundreds of hours; stand-by equipment is provided for the repair period so that the dispatcher does not go blind. The method of loading is based on using the RTCS equipment for performing other functions of the automatic dispatch control system.

For instance, the RTCS stand-by equipment may be loaded with certain short-term planning problems. This technique is employed at the EdeF National Control Centre where one of the control digital computers is converted into a scientific computer by modifying the main and adding auxiliary equipment. The equipment may be regarded as a single complex without dividing it into the RTCS and CC facilities. On such occasions the inoperative machines are used for planning, but it is difficult to organize the work. The functions of the RTCS equipment usually include presentation of information and direct digital control (e.g. LFC-AGC—load frequency and automatic generation control), and the scope of immediate calculation assistance to the dispatcher is limited.

System structure. Let us consider a general structure of the man-machine system operating on a real-time basis inherent in most of the RTCS (Fig. 4.1). Thick lines show the main loop of the system and its components, thin lines, auxiliary elements and links. The main loop includes:

—a computing system with hardware, software and data bank (information base of the system);

—input/output devices (main) called with their application programs a man-to-machine interface;

—the dispatching center operating personnel who receives information supplied by the machine, takes a decision independently or with the help of the machine, and transmits it to the object;

—the controlled object with equipment and personnel for carrying out the required operations, as well as transducers and transmitting equipment for supply of information to the computing system.

Auxiliary functions are performed by:

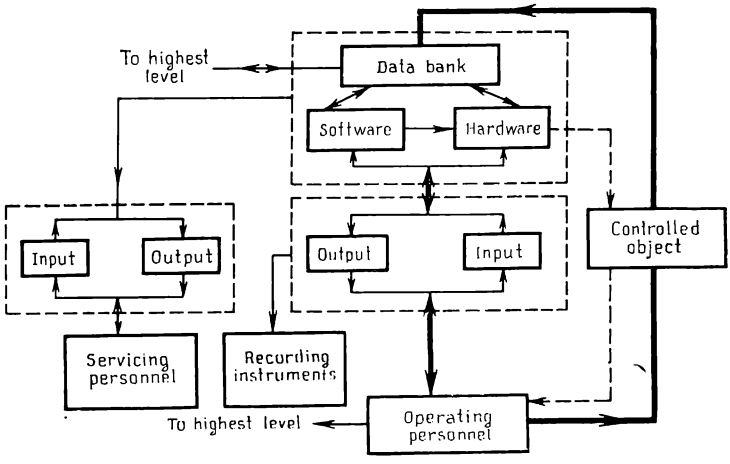


Fig. 4.1

—the servicing personnel consisting of hardware specialists and system programmers who ensure normal functioning of the system and introduce the required revisions and additions to programs and data;

—input/output devices for the servicing personnel (the system programmer's console and the synoptic panel);

—devices for data logging, activated both by the operating personnel's orders and directly by the commands arriving from the computing system.

The links between the computing system and the object, as well as between the object and operating personnel (bypass the system) are also of an auxiliary nature (shown in dashed lines). Some of them present a direct digital control already used in the modern systems, as well as actions to change settings of autonomous systems. The other links show the possibility of furnishing information to the operator of the power system (dispatcher) by-pass the computing system. It should be noted that such links (acting independently by-pass telemetry loops) were regarded principal before implementation of computers and no operations were allowed before a confirmation was received over the telephone.

System functions. The functions to be performed by the operating-information complexes of the power system dispatching centers are strictly defined at present. For all the dispatching control levels these functions include:

1. Acquisition, processing and presentation of data. The data acquisition is effected by the SCADA (Supervisory Control and Data Acquisition) systems. All information is immediately trans-

mitted to the computer. Here the data are subject to validity check, rated (scaled), formed into arrays and stored for further presentation, recording and calculations. The computer loading is determined by the number of points scanned in the cycle, the cycle duration and number of different images (formats) to be prepared for display on the CRT screens. On some occasions the machine also controls the board, so that its load increases.

2. Forecasting of emergency conditions of the system (contingencies evaluation). Meant by this term is calculation of flow distribution in the system as applied to given load conditions in case of possible changes in the network (cut-out of generators or power lines). The calculations are performed at the dispatcher's discretion periodically with automatic exhaustive search of probable variants and analysis of the results obtained. They provide for estimating the probability of current overload and (indirectly) stability margin. However a direct problem of stability evaluation, which requires high computing capacity has not been solved yet within the framework of the RTCS.

3. Recording of state variables automatically or by the dispatcher's command. The so-called retrospective analysis with freezing and unfreezing proves very convenient. It resides in that while observing on the CRT screen successive states of the power system stored in the computer temporary memory, e.g. during the recent accident, the dispatcher can give a command to freeze the presentation of the events, automatically fix the state of the system at that moment for a register, and after unfreezing playback, keep on his analysis. Depending on the memory capacity of the computing system and some other factors such "rewind" with subsequent playback may cover a maximum of 30 min.

In addition to the above, the higher level DC computing systems provide for:

—economic dispatch according to load forecast for a particular period (usually 5, 10, 15 min). The results obtained are displayed for the dispatcher: they may be sent to the respective stations and, if the LFC-AGC facilities are available, act upon the data points of the analog control systems or be used at a direct digital regulation;

—record intersystem load flows subject to billing.

Such bills should be paid in view of the nature of the exchange (economy, emergency, etc.) which can be easily discriminated by the computer contrary to regular counters. This circumstance was decisive for many US pools which started working with free load flows.

At the same time the lower level dispatching centers serving small power areas have their own tasks that will be considered below.

Methods of ensuring reliability. The reliability of modern computer hardware is fairly low, it is approximately an order as low as the reliability of the main power equipment. This is especially applicable to the electromechanical input/output devices, etc. which operate at high speeds and perform sufficiently complex operations. The attempts to increase reliability solely by improving quality of the equipment yielded insignificant results. The principal way to ensure reliability today is proper selection of the structure which should be redundant.

Meant by "redundancy" is introduction into the system of additional units or elements constructionally similar to the primary ones, which are held inoperative or perform backup functions but substitute the primary elements in case of their failure. The redundancy may be full or partial, with automatic activation or manual connection of backup elements.

Full redundancy. An example of a full redundancy (Fail-Save) system with respect to primary functions may be the system which serves the National Control Center of the CEGB of Great Britain. It uses the ARGUS-500 computers by the Ferranti Ltd (its block diagram is shown in Fig. 4.2). The system comprises two identical sets of equipment (*A* and *B*) which are enveloped by two systems of buses sectionalized and grouped in such a way that each of peripherals *B* may be connected with each of the processors (the only exception is the magnetic disk memory MDS which is not present in set *A*).

There are also the magnetic drum (*MDrS*) and tape memories (*MTS*). The system has two telemetry inputs and four display outputs; at least two CRT connected to each of the outputs are installed at each dispatcher's desk. The failed equipment is discarded and substituted with OK one automatically for which purpose special multicontact "corridor" relays are provided.

To detect faults, in addition to supply of special tests (in turn with primary information), use is made of a special watch-dog device, a timer which supplies check signals and if no response is received at a predetermined time, gives a command for appropriate switching. Such a method is also used for checking the bus and processor systems. The display control functions (primary) are normally executed by processor *A*, while the aid functions, by processor *B* (it includes the disc memory for the purpose). In case processor *A* fails, processor *B* ceases the aid routine and changes over to the programs of processor *A* thus ensuring 100% backup of the main functions.

Partial redundancy. Partial redundancy (Fail-Soft System) is coupled with deeply modular structure of the system whereat failure of one module means only certain "fading" of system functions, and the greater is the number of such modules the lesser is said fading. An

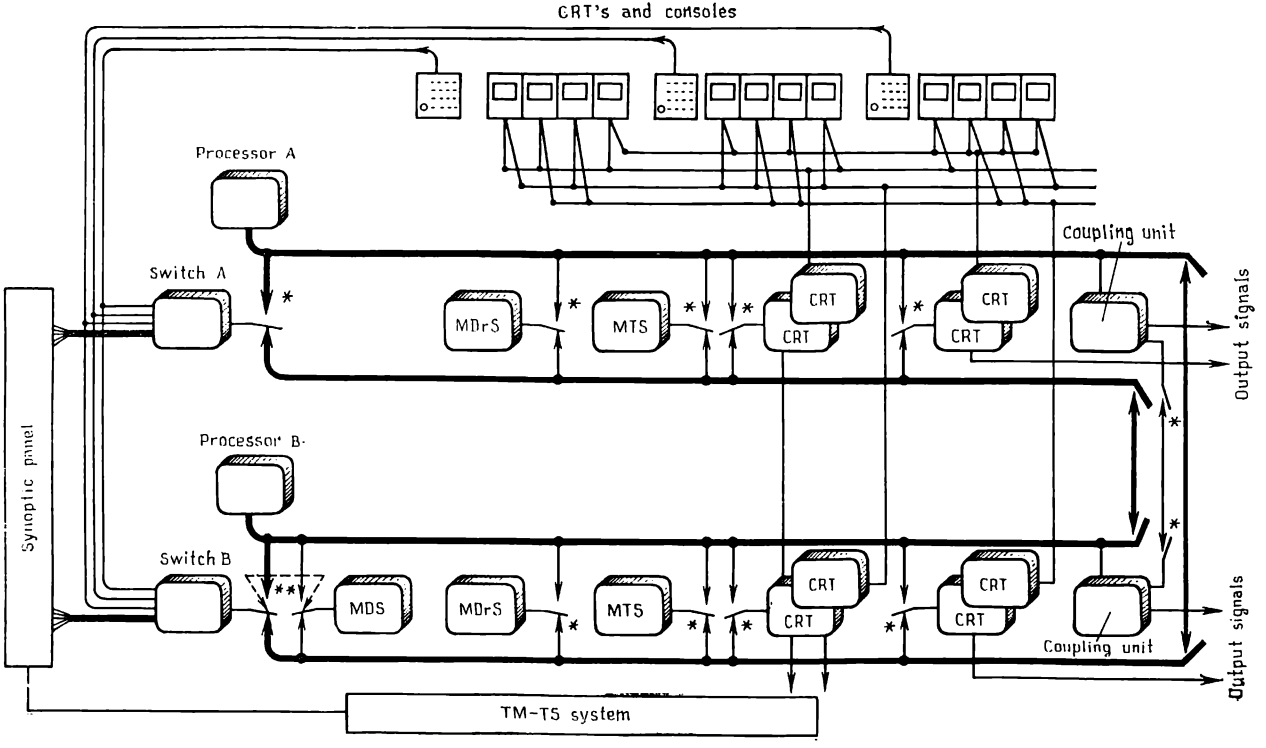

CRT's and consoles
Processor A
Switch A
Coupling unit
MDrS
MTS
CRT
Output signals
Processor B
Switch B
MDS
Synoptic panel
Coupling unit
TM-TS system

Fig. 4.2

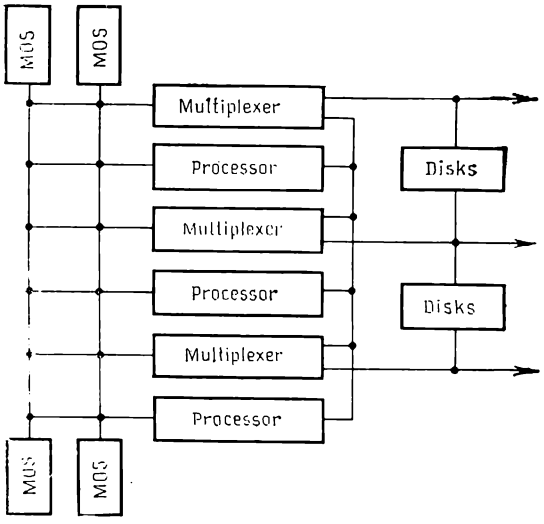


Fig. 4.3

example of the partial backup system is the B-6700 Fail-Soft system made by the Burroughs Ltd. for the Philadelphia Electric company (Fig. 4.3). Here all the elements of main frame of the system (processors, memory, channels) are divided into 3-4 modules with a complete interconnection capability (each has access to each). There is also a special reconfiguration cabinet which carries out elementary diagnosis and disengages the faulty element. This is immediately reported to the master control system (*MOS*) which reallocates the workload so as to exclude or extend execution of functions which are of least importance for a given configuration.

In the particular case the general capacity of the system is very high and auxiliary functions are usually cancelled. However cancelling of primary functions is also possible. For instance when displaying a complete diagram of the system, it is sometimes reasonable to omit presentation of separate substations, etc.

In addition to the above-mentioned method of increasing reliability, to eliminate malfunctions, the B-6700 Fail-Soft system uses special technique residing in that all information from the MOS is relocated to the disks and then inserted to other memory modules and transmitted to other processors. The "Fail-Soft" name of the system is also applied to the partial redundancy method as compared with the "Fail-Save" full redundancy method. If using corresponding phenomena of the power system operation, it is possible to say that full redundancy is equivalent to the use of stand-by units and partial, to frequency load shedding.

Equipment. Despite considerable similarity between the RTCS configurations in different ADCS (the full redundancy circuits as shown in Fig. 4.2 are most frequently used) and comparatively low difference in workload (the controlled power system usually comprises 400-700 lines with 250-450 nodes in the network and the RTCS functions are almost fully identical), the capacities of the computing equipment differ radically. This difference stems mainly from different approach to the possible expenditures for such equipment and unequal capabilities of computers as of the year of delivery; said difference is compensated for by the difference in the calculation methods used and in their cycles. The possibility of such a compensation, i.e. adaptation to the equipment available, is one of the most vital features of the computerized systems.

Let us consider the RTCS based on small (process control) machines. The USSR system using such machines is described in Chapter 3. Abroad, such computers were installed in three large grids between 1967 and 1969 (Table 4.2).

Table 4.2

Country	System	DC level	Computer type	Number of bits	Operation duration, μs	
					addition	miltiplication
France	Electricite de France	National Zonal	C-90-40	24	3.5	7.0
England	Central Electricity Generating Board	National	Argus-500	24	3.0	10.6
USA	New England Power Exchange	Super-pool	Sigma-2	16	2.3	10.3

These RTCS are successfully operating at present with performing substantially all the necessary functions. For instance, the British National Control Center system receives at least 1100 telemetry data and 400 signals with preparing on their basis up to four different presentation formats simultaneously, and additionally performs some calculations. Calculation of three-phase short circuit currents for checking short circuit power at different points of the power system under given load conditions requires from 4 to 5 min and is performed with an interval of 30 min. Contingency evaluation for the case of emergency cut-out of system elements (up to 500 variants for the network comprising 500 branches and 300 nodes) takes 10-13 min and is carried out with an interval of 20-30 min.

In the USA, on the contrary, the volume of calculations is decreased (when using a small computer) but a direct digital control signal is supplied every 2 seconds to 16 generation units and summarized signals in the form of relative increment of desired generated and exchange powers for four groups of pool utilities are fed. Said signals are generated on the basis of economic dispatch calculations according to the equal incremental cost loading technique taking into account line constraints under normal and emergency conditions, reserve power in separate areas, etc.

To perform such a diversity of functions by machines without floating point, it is necessary to simplify the methods of calculation and increase its cycles. For instance, in the above-mentioned real-time load flow calculations for different variants of network carried out in England, the nodal admittance matrix is not inverted at transfer from one variant to another but is corrected only (precise inversion of the matrix occurs once a day), and the telemetry data are received with a cycle of 30 s. This naturally decreases the accuracy of calculations and extends their period. Therefore, the English control engineer is allowed to address the CC system through a terminal. In France one of the machines installed in the National Control Centre has improved characteristics (in particular, floating point capability), while the above-mentioned US power system has an additional analog-digital computer.

When average-capacity all-purpose machines are used in the RTCS, their additional functions are usually planning calculations. As regards the real-time functions and problems, they remain similar to those of small computers. However some details are different. For instance, the main links between separate power systems have a decreased interchange scanning cycle (up to 2 s) and in addition to a high-speed program for calculating load flow in the 200-node network (said program being primarily intended for emergency use), provision is made for utilizing the program in determining complex flow distribution within a 400-node network, etc.

The average capacity machines of the "Sigma-3" and "Sigma-5" type manufactured by the "Xerox" Corp. are used in the USA. The "Sigma-5" has a speed of action approximately twice as high as that of the IBM-360/50 machine at considerably lower cost achieved by a number of simplifications. An example of a system with a great number of such computers installed at different objects are the utility in the state of Arizona (twelve "Sigma-3" computers) and one of the utilities in Pennsylvania (eight "Sigma-5" computers). The machines are superior in the advanced channel processors oriented to the use in the real-time systems.

Large computers with a speed of action of about 500 thousand operations per second were initially installed in the RTCS between

1971 and 1973. An example of such systems are the above-mentioned system of the Philadelphia Electric company using the B-6700 Fail-Soft machines, which implements a complex algorithm of economic dispatch in view of actual characteristics of the turbines, and a system used at the control center of the Bonneville Power Administration. The latter system includes about 30 hydroelectric stations, hence a great bulk of hydromet information.

Therefore, substantially two systems are established, one of which (SCADA—Supervisory Control and Data Acquisition) serves for acquisition and front-end processing of network information and the other (RODS—Real-Time Operations, Dispatching and Scheduling) performs all the necessary calculations including economic dispatch and required voltages in the network, controls the system display operations and supply of the respective signals to the hydroelectric and thermal power stations. To effect this, the SCADA system includes two GE PAC-4010 computers and two GE PAC-3010 front-end processor and associated remote terminals, the RODS system has two large computers of the PDP-10/55 type and three modified minicomputers of the PDP-11/15 type.

Interface Systems. According to a generally-adopted classification the dispatching center systems considered in this chapter relate to the real-time systems but are at the same time very specialized systems. All of them have similar features such as a high redundancy level, presence of two or three bus systems (which can be compared with the buses of electric power stations or substations), linkage with telemetry and data transmission devices at one side, and with display devices at the other side, etc. Such features are known to be ensured when using standard equipment only if correctly selecting its configuration and software. However this will inevitably lead to certain redundancy since the general-purpose equipment comprises some units which are not needed for a particular configuration. The same is applicable to the utility programs which organize functioning of the system.

There exists another way for creating interface systems, based on the use of standard (general-purpose) and non-standard (special-purpose) equipment in such systems. This way requires participation of agencies specialized in the computerization of one or several allied spheres and is implemented by creating special interface systems. One of such systems developed by the TRW Inc. of the USA and having a trade name of "System-9" is shown in Fig. 4.4.

As seen from the figure, the system comprises a circuit the input of which is connected to an all-purpose computing system, while the outputs are the circuits of the telemetry, communication, display devices, etc. The circuit per se comprises the required software and hardware controlled means for switching and debugging the channels. There are several modifications of the system which are structurally

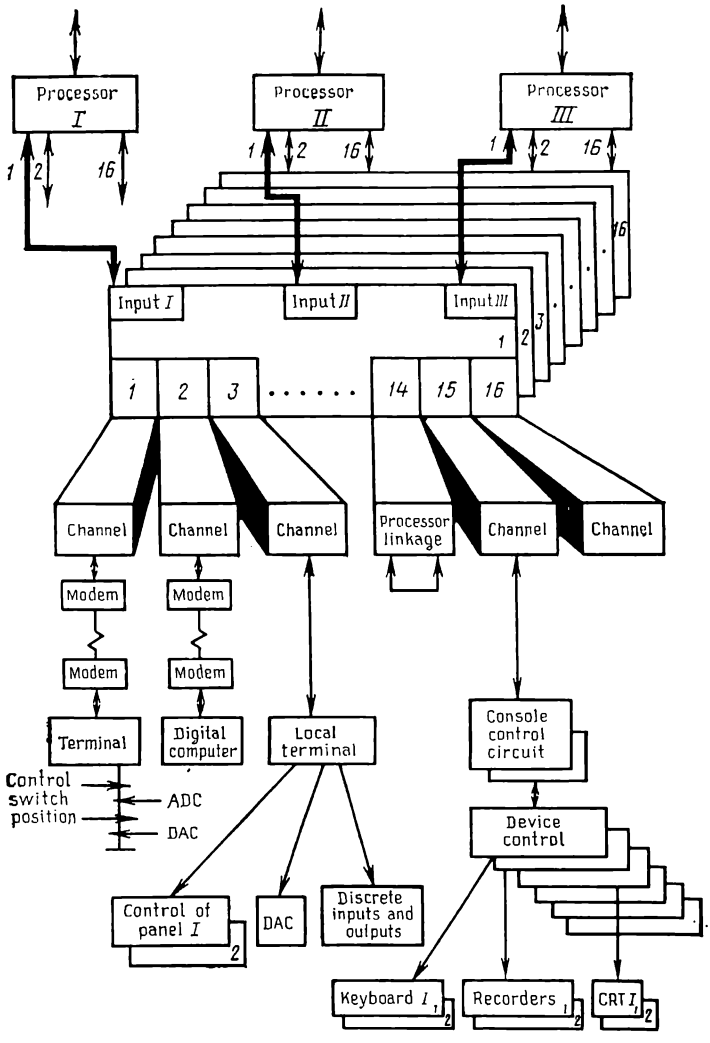


Fig. 4.4

identical but are adapted to the all-purpose computers of most frequent use: IBM-360/370, "Sigma 2/3/5/7", Burroughs B-6700 Fail-Soft, PDP-11, and some others.

Special programs intended for serving a corresponding computer were elaborated for the "System-9". These programs similar to hardware are developed beforehand and are only corrected, if necessary, to be in line with specific features of a particular power

system. If there are a plurality of identical consumers, such an approach proves to be economically feasible and provides for 25-30% cut in system cost with reduction of their implementation periods.

In addition to the devices arranged at the dispatching center, the equipment of the "System-9" includes receiving devices (terminals) for stations and substations. Such devices may be regarded as conventional elements of control systems, the only difference residing in that they make allowance for specific features of the hierarchic structure with a direct digital control. This calls for the local personnel to be able to converse with the system at the DC by inserting such data as equipment readiness for starting and participation in the AGC procedure, unit load limits, etc.

In the automatic mode the system should inform the personnel of its actions and, in some cases, produce respective commands. If the system activities are confined to automatic changes in set points of some local adjustment and monitoring loops, it is convenient to arrange the equipment of such loops at the terminals jointly with the controlled object status transducers, the indications of said transducers being furnished to the personnel. Thus a single physical and logical structure is created which facilitates designing of the system, preparation of programs and operation.

RTCS effectiveness and ways to increase it. Functions of the power system DC RTCS are still very limited. While successfully executing the tasks of data collection and presentation, they do not pay back for high capital investments which approach the cost of 50-100 MW installed capacity at modern thermal power stations. Therefore, the problems of effectiveness of such systems are very urgent.

It was expected that implementation of such systems would primarily contribute to increase of the economic efficiency of power grids owing to real-time optimization of their regimes ("post-optimization" to be more exact, since the optimum schedules are assigned in the course of planning and are only refined in practice when the actual load of the power system differs from the forecasted one). However at present this holds true only for power systems with a great number of hydroelectric stations where optimization of river discharge is possible.

In the case of thermal power station systems with similar high-efficiency equipment, the effect of post-optimization may result mainly in lower loss in the network, and be insignificant. Therefore, when evaluating such systems, their basic effectiveness is usually regarded to be an increased reliability of power supply. To be more exact, the general problem of increased power system reliability involves a number of sub-problems solved by appropriate automatic means. An important part in the solution of said sub-problems is played by the AGC and special automatic devices which preclude overloading of weak links and return the system

conditions to the permissible domain.

Therefore, a dispatcher can use the RTCS only to take measures that were not taken by the automatics for some reasons. There are, however, some aspects of the system reliability problem which are almost unaffected by the automatic equipment, i.e. less intense initial conditions with respect to most probable breakdowns, accelerated post-breakdown recovery of the system, and decrease or elimination of accidents caused by personal errors. All these aspects are linked, in one way or another, with the work of the dispatcher, and the OIC may help to him in this respect. Therefore, main efforts are presently made in this direction.

Some trends emanated from the experience with such systems are as follows. Logic for tracking electrically interconnected circuits at presentation of substation diagrams was introduced at the National Control Centre of CEGB. This simplifies orientation of the dispatcher at division of the system. The RTCS at Houston Power & Light Comp., USA, features remote control of switches with the aid of a light stylus on a display. Touching a switch symbol on the diagram after depression of the action key causes cut in or out of the switch. This precludes errors in manipulating the switches. In the RTCS of the New-York power pool and PJM Control Centres, any line overload, actual or forecasted, is immediately presented on the board. The line symbols are made from fiber light guides linked with different color light sources which are controlled by the computer. A similar technique is used at the National Control Centre of EdeF, where $l/4$, $l/2$, $3l/4$ and l of the line symbol light up depending on the actual load of the line.

Apart from the above methods of improving effectiveness of the DC equipment by increasing throughput capacity, there are methods aimed at decreased calculated workload in computing systems with corresponding reduction of their cost. For instance, it appeared possible to perform calculations of power line overload hazard not cyclically (periodically) but sporadically by the signal of significant change of the transmission angle vector in the system. This signal is generated at statistic processing of telemetry data (state estimation). It arrives far more seldom than the command for periodical calculations. Thus the computer speed of action may be decreased.

Computerization makes it also possible to reconstruct some parameters of the network conditions not found among the direct telemetry data for some reasons, thus making cheaper the telemetry system. Also important is an indirect effect of increased flexibility of the system: facilitation of operations for supplementing, modifying and simplifying the supervisory control. Such methods provide for approaching the desired target to some extent. If the main effect

of the RTCS is expected to be in the improved reliability of power systems, such complexes should meet the following requirements:

(1) fast simulation of the power system both in steady state and transient conditions when determining its stability margin in view of the emergency control schemes operation;

(2) fast determination of probability of a serious breakdown with due regard for weather, equipment condition, etc.

(3) automatic tracing and correction of emergency control schemes set points according to the current conditions and breakdown probability.

To meet the above requirements, it is necessary to develop means for ensuring fast simulation (the hybrid systems seem to be the most promising ones at present) and elaborate procedures of breakdown probability analysis and automatic selection of set points for the automatic equipment. The corresponding RTCS may be of great help in this respect as collecting massive statistics and providing for a part of the computer time to be used in automatics experiments.

4.4. Computing Equipment at Power Stations and Substations

Similarly to other enterprises the power stations and substations need supervision over the production and economic activities and technological processes. The technological processes of the power industry are very complex owing to their continuity and high reliability requirements.

Economic management is simpler to perform owing to homogeneity of power produce and comparatively small staff. When carrying out economic management the stations and substations may be regarded as part of another greater object (power administration, network region) and be served primarily by the terminals from the central systems (though some problems may be solved in situ). Therefore, in power industry management the technological process automatic control systems require uttermost attention.

The station and substation control systems are usually created as complex facilities comprising a single set of equipment, and capable of solving a plurality of problems relating to different time moments. It is also possible to adapt computers for solving economic problems by allocation of a part of the machine time. The control problems may be divided into several groups (subsystems). The main problems are as follows:

— control and monitoring of the power object equipment (unit or sub-assembly level);

— control and monitoring of the entire object as a part of the power system (system or station level).

Another group of problems may be divided, in turn, into:

— control and monitoring under normal operating conditions of the system and slow changes thereof;

— control and monitoring under abnormal and drastically varying operating conditions.

Thus, there are problems on the unit, station and system levels which may be referred to as the first, second and third grade problems.

Historically, the computerization of power stations and substations began with solution of the first grade problems at thermal power stations (later at atomic power stations) and of the second grade problems at hydroelectric stations. The third grade problems are being solved now on most occasions when using the SCADA systems only for remote control over small unmanned substations. More complex systems are only originating now.

First grade problems. These include primarily the problems of controlling the thermal power generating equipment of power stations and auxiliary drives of the electric part of stations and substations. In this case a plurality of points are monitored (up to 3 000 points per power unit of a modern thermal station and up to 5 000 for an atomic power station), and functioning of different regulation systems (fuel supply, combustion systems, etc.) is ensured, said systems being of a discrete (impulse) nature similarly to a digital computer. The speed-of-action requirements are moderate and embodiment of the centralized system concept is quite natural to handle such problems.

Four periods may be defined in the development of systems for solving the first-grade problems:

(1) the late 1950s—formulation of concepts, investigations, economic justification;

(2) 1961-1969—experiments, installation of second-generation computers at some stations for checking parameters (the so-called information mode) and program controlling secondary non-essential equipment;

(3) 1970-1973—installation of third-generation machines for program controlling non-essential equipment during operation of power units and major equipment at power unit start-ups and shutdowns Gradual transfer to direct digital control in main loops with expelling the old equipment;

(4) 1973-1976—introduction of CRT displays into the systems, appearance of a plurality of specially designed computerized control systems and wide-scale implementation of the latter.

In future specially designed systems are expected to be manufactured in lots, and find wide application.

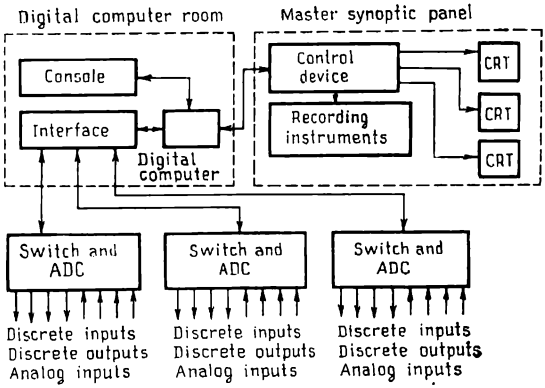


Fig. 4.5

A special-purpose computer, type ИВ-500, manufactured in the USSR, is designed for monitoring the thermal power station units. The "Argus-500" machine is used in Britain for controlling a number of thermal and atomic power station units. The "Prodac-250" system based on the "Sigma-2" computer is employed in the USA.

A typical configuration of such systems has been finalized by now and includes three main parts:

(1) a central part or main-frame, arranged usually in a special room referred to as the "computer room";

(2) remote terminals (RT) in the form of cabinets with normalizing (scaling) circuits, switches and other gear arranged in close proximity to the object, often at different zones thereof;

(3) control board equipment, including communication interface and accessories.

The block diagram of the system (Fig. 4.5) shows that such a configuration is very advantageous. Actually the remote DA scanning (polling) of the inputs and outputs of the object links provide for drastically decreasing the length of cable lines from relays, transducers and actuators. A relatively small number of cables intended to transmit only 1 byte in both directions are laid from the switches to the computer room and from the computer room to the control board. The cable should include 24-32 conductors (including stand-by ones); besides several special power supply and telephone cables are needed. Consumption of cables is usually 15-20 times as low as in the case of individual circuits.

Installation of CRTs on the control board is also economically feasible. It replaces numerous instruments, lowers cost of boards and other expenses. At the same time the cathode ray tubes facilitate and improve quality of the operator's job, and make it possible to solve some new problems.

During solution of such problems signals from thermal and mechanical parameter transducers (pressure, temperature, flow rate, etc.) are fed to the analog-to-digital converters of the remote terminals. The power transducers insert information on electrical load of the unit and power consumed for its auxiliaries.

This provides for determining basic technoeconomic indices of the equipment, such as specific consumption of equivalent fuel per 1 kW h of power generated, unit efficiency, consumption of electric and thermal energy for own needs, etc. These calculations are carried out in the course of work (on-line) and are used for improving the above indices and eliminating equipment troubles, e.g. those which increase energy consumption for own needs ("leakages", etc.).

Another important trend is to use computers to accelerate starting operations of power units, and prepare them for loading. High temperature of steam used in modern turbines necessitates thorough initial heating of the power units before starting so that the difference in thermal expansion of its parts having different temperatures does not cause breakdowns or accidents. The unit is gradually increasing the steam temperature and pressure and turbine speed; this operation currently takes 4 to 6 h.

The long duration of this operation becomes a decisive factor in selecting the unit operating conditions during drops of load (stoppage or near-idle operation with inevitable losses). The use of computers provides for determining by special calculations and automatically maintaining the optimum rate of loading at different stages and decreases both the time of loading and labour consumption which is usually very high at these periods.

The unit-level machines may be utilized at all modes of thermal power stations, both load and start-up, facilitating personnel job and improving effectiveness of the units.

Second-grade problems. These problems encountered primarily at hydroelectric stations are divided into *information* and *optimization* problems.

The information problems are linked with large sizes of hydroelectric stations arranged along the river bed or dam. The length of such stations abreast of the units amounts to several hundreds meters, while their substations usually erected on a high bank of the river extend the information links to a kilometer. Besides, hydroelectric stations include more power units than thermal stations (12-20 against 6-8). On the other hand, the technological process is relatively simple which allows for decreasing the personnel and carrying out main control operations from the master control panel (MCP) where all the necessary information is concentrated. Therefore, despite a considerably smaller number of parameters measured at each unit, the total volume of information is rather

high at hydroelectric stations and expediency of using peripheral remote terminals (RT) for decreasing cable lines is obvious.

The external RT embodied short-range telecontrol devices which collected information and transmitted it to the MCP in the form of pulse code signals. Such RT are presently installed at big hydroelectric stations.

Alongside with the short-range telecontrol devices and even earlier, special automatic units were developed for hydroelectric stations, intended to relieve personnel of some auxiliary functions which is significant in case of a great number of power units. The automatic units combined program timers for supplying pre-inserted data on the scheduled load of a hydroelectric station as a function of time, and group regulation devices for maintaining the required power level of the generating units. Such automatic units were called HPS automatic controllers, and it was planned to make them capable of optimum distribution of load in view of individual characteristics and peculiar conditions of separate units.

Development of digital computers revealed that the services offered by the short-range telemetry device and automatic controller can be integrated in one unit. Originally those were devices consisting of the RT and a central part with advanced logic capabilities which permitted detection of parameters fallen beyond the permissible limits as well as print-out (recording). Those devices were called logic machines. At present all-purpose digital computers are widely used at HPSs instead of short-range telemetry devices, automatic controllers and other separate devices (e.g. those intended to start generating units, control some auxiliary mechanisms, etc.).

Implementation of computers completes an important stage in integrated automation of hydroelectric stations, control of their equipment in regular modes and transfer to a new stage linked with prevention and elimination of emergencies. This stage seems to require installation of station level machines at thermal and atomic power stations.

Third-grade problems. These include the problems that were encountered and complicated in the course of power system development and have become very urgent to-day:

— events recording;

— implementation of protection of various kinds;

— implementation of line automatics, including automatic tests of power lines and transmission restoring in case of self-clearing of faults;

— emergency control including prevention of system falling beyond the permissible operating limits and return to normal conditions.

The events recorded at stations and substations are cut-ins and cut-outs of power lines, operation of protection and automatic

devices, appearance of various alarm signals (e.g. signals from insulation monitoring devices, etc.).

Usually the above events are entered into the operating log of the station or substation with subsequent transfer of respective information to higher levels of operational management. The operators who make the entries receive information on the events from different signalling devices (annunciators, light panels, etc.). As the number of the control devices and that of the objects controlled by them increase, the volume of information grows and the operators cannot manage it all; besides, arrangement of such devices, which are numerated in hundreds at modern stations and substations, is rather a problem. Therefore, the processing of information at stations and substations requires installation of the so-called "event recorders". These are special loggers which mark the time of operation of a certain discrete automatic device with indicating its number or code.

Such loggers, including high-speed devices adapted to power industry requirements are commercially manufactured to-day. Employment of such loggers at a number of trunk lines (e.g. 500-kV main lines) has revealed that the most efficient way is to install general-purpose computers with a main memory of 30-50 K bytes and cycle of not above 1.8 s, capable of logging up to 400 contact makings and additionally supplying signals (without recording) for 600 contacts more.

The priority interrupt mode is expedient for logging, while low speed of action of the output teleprinter (10 characters per second) necessitates the use of a memory buffer zone for 100 events. At the same time, the contact made signals may be supplied in the constant scanning mode since polling thereof once per second will occupy not more than 1% of the processor time.

In addition to logging and recording (printing in clear text message), precise time is marked. To effect this, special signals are transmitted from the system center via communication channels and are modified at substations by introducing correction for premeasured velocity of their propagation. Therefore, resolution of logging is limited only by the need for special relays intended to isolate the computer circuits from the control current circuits. Complete resolution of logging is about 10-20 μs, but can be increased up to 1 μs.

After logging all information is transmitted to the dispatching center of the system via regular teleprinter channels at a speed of 50 bauds and is accessible for further use. Besides, the logging computer stores all information on the status of the system area adjacent to the substation and may be employed for other purposes.

Another reason that promoted computerization was the quest for simplification of creation and improvement of functioning of

plant groups (clusters) controlled from one center and made up from a number of unmanned substations or stations of relatively low capacity. In the USSR on such occasions use is made of the methods for increasing the level automation of the objects at a relatively limited volume of telemetry. In the USA, on the contrary, telemetry is widely spread, while installation of a computer at the group control center and of its terminals or similar machines at the controlled plants provides for solving the problem with a substantial utilization of standard equipment.

Depending on the cluster size and nature of plants served, such a system approaches the DC systems to a certain degree as regards the functions performed. Therefore we shall not discuss the functions but consider the possibilities of implementing a direct digital control of the group. In addition to certain secondary operations, such as switching over of transformer taps and banks of static capacitors, carried out to-day at some unmanned substations, the computers are being more intensively employed to control switching procedures.

The activities of the US Westinghouse Electric Corporation for implementing direct digital control to perform relay protection functions resulted in creation of the "Prodac-70" installations based on small control computer, type P-2000 (16 bits, memory cycle of 2 μs, hardware multiplication). The installation was adapted to storage battery supply (through a 3-kW inverter) and connected to current and voltage transformers through a 16-channel analog-to-digital converter which was connected to each channel in every 0.5 μs. The program inserted ensured three-stage remote protection against inter-phase shorts or grounding; to speed up determination of current value at the moment of short, current derivative was measured on the assumption that it was purely sinusoidal.

Tests of the installation on a transmission system model and one 220-kV power line proved the correctness of its principles; nevertheless, such installations have not found wide application. A similar installation using the "Argus-500" computer is arranged at one of the atomic power plants in Britain for automatic reclosing at the 154-kV power line.

Interesting results were obtained at the Votkinsk Hydro in the USSR from the employment of a small computer with a program inserted in a read-only memory (ROM) for controlling emergency control schemes. This machine, type УМ-1НХ, has a ROM for only 256 words; nevertheless it executed a sufficiently complex algorithm for preliminary preparation of disconnectable power depending on the breakdown nature.

Thus the possibility of executing sufficiently complex automatic functions with the aid of computers has been proved. However to ensure wide-spread application of such machines, a number of

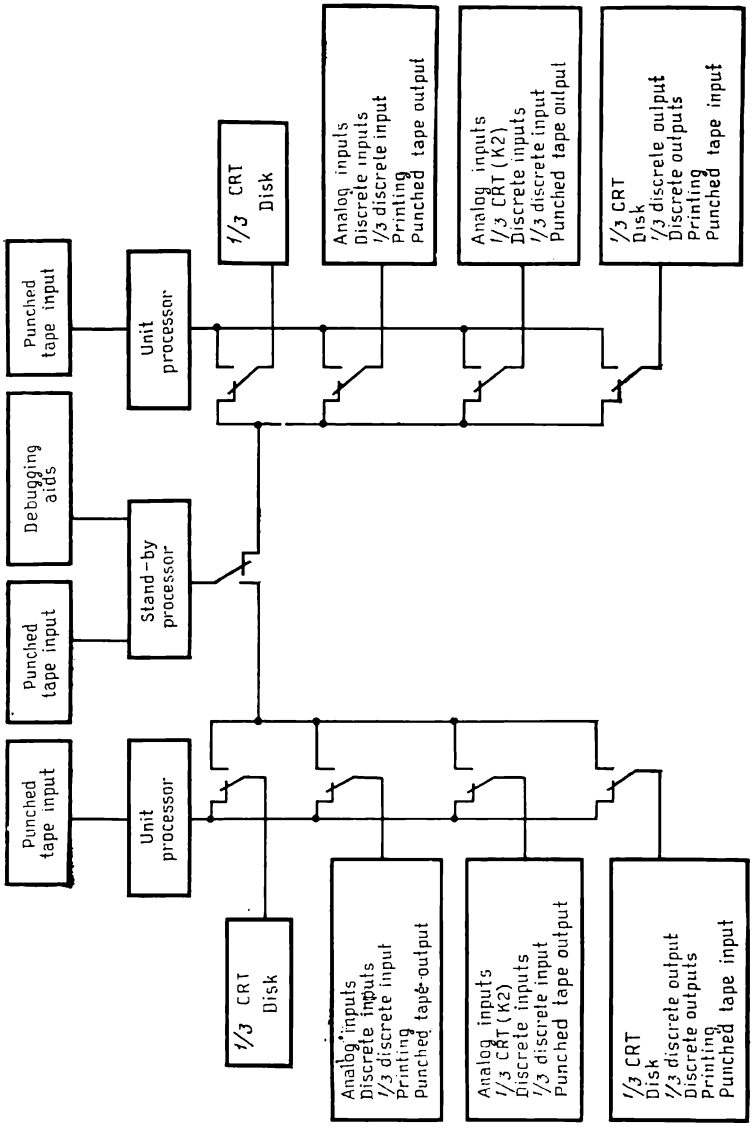

Punched tape input
Unit processor
1/3 CRT Disk
Analog inputs
Discrete inputs
1/3 discrete input
Printing
Punched tape output
Analog inputs
1/3 CRT (K2)
Discrete inputs
1/3 discrete input
Punched tape output
1/3 CRT
Disk
1/3 discrete output
Discrete outputs
Printing
Punched tape input
Punched tape input
Debugging aids
Stand-by processor
Punched tape input
Unit processor
1/3 CRT Disk
Analog inputs
Discrete inputs
1/3 discrete input
Printing
Punched tape output
Analog inputs
1/3 CRT (K2)
Discrete inputs
1/3 discrete input
Punched tape output
1/3 CRT
Disk
1/3 discrete output
Discrete outputs
Printing
Punched tape input

Fig. 4.6

reliability and effectiveness problems are to be solved.

Methods of improving reliability. It was noted above that reliability of computerized system is ensured to-day primarily by structural redundancy. This is characteristic of the methods considered herein, while the presence of direct digital control circuits with a relatively high speed of action makes the reliability requirements more stringent (it is necessary to exclude any uncertainty of the final decision or even occasional malfunctions caused, e.g. by switching over from one peripheral devices to the other).

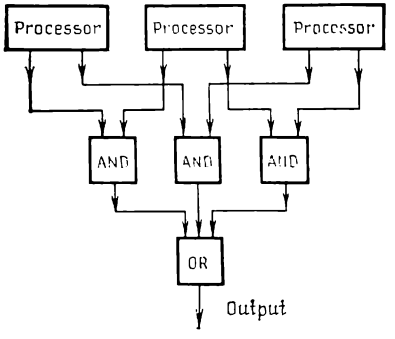


Fig. 4.7

The experience of computerization has led to a sufficiently feasible "tripartite circuit" the unit-level presentation of which is given in Fig. 4.6. The circuit uses three processors for two power generating units, of which one is a stand-by processor constantly connected to special devices for testing the equipment. Two others are the working processors participating in control of the respective units. If the working processor fails, the stand-by one immediately starts functioning. After switching over the required peripheral devices to itself, the processor reads all necessary information from the disk and starts executing the functions of the primary processor.

The circuit is distinguished for "splitting" of external devices and real-time hardware (analog-to-digital converters, discrete inputs and outputs). The entire set of such equipment is divided into 2 or 3 groups of similar units which are then distributed among four arrays shown in the diagram. This distribution corresponds to connections of inputs and outputs with particular transducers, relays and actuators. The faulty circuit information flow is compensated for to the required degree through the OK circuits. If the indirect methods fail to yield good results, duplication is used with observing the least risk principle.

The second-grade problems are characterized by two-processor circuit similar to that used at the DC (see Fig. 4.2). For the third-grade problems, where a false action linked with inadvertent malfunction of the machine is irreversible, while program check methods do not offer a 100% guarantee, use is made of the so-called majority systems (Fig. 4.7). These systems contain three identical sets of equipment solving the same problem, while the output signal is generated by special logic circuits on the "two of three" polling

principle. In this case, to check faulty peripheral devices and ensure processor redundancy when using the majority systems, at least one more processor should be provided at the object and connected to the set of debugging aids.

4.5. System Effectiveness at Plants and Ways to Improve It

The effectiveness indices are more vital for the object systems than for the dispatch control centres (DC) ones.

In contrast to the DC systems and especially to the computing centres (CC) ones, the object systems have a few problems which cannot be solved by conventional means without a computer. It is usually impossible to economically justify the need for providing complex and reliable redundant systems with a great number of auxiliary devices. Such a need may be reasoned by the possibility of a simultaneous replacement of all or almost all equipment of the control system by a centralized computing system. If the computing system is fully loaded and original expenses for programming have already paid for themselves (e.g. at a re-use of the majority of programs), the system will be always cheaper than the plurality of apparatuses of various types and makes operating in parallel. Both the structural redundancy mentioned above, and equipment duplication are of vital importance for such a system. For instance, if the system includes 150 discrete inputs, it may appear that a 256-input module has to be taken since the nearest smaller module contains only 128 inputs. This facilitates development of the system though initial comparative evaluation may be not in its favour.

To determine effectiveness of such systems, their loading should be primarily calculated. Consider the first-grade problems. According to all afore-said, loading of the computer with the above problems is sufficiently high and structural redundancy may be minimized (1.5 system per power generating unit). Therefore, further development of unit-level control systems without computers, e.g. for atomic power stations, is substantially impossible.

The computer loading for the second-grade problems is not high to-day but it can be considerably increased if the technical diagnostic systems are organized. Solution of the third-grade problems is characterized by the following. The relay protection, line and mode emergency control equipment installed at the stations and substations and serving neighbouring regions is becoming more and more complex.

However the power system problems are complicating still more rapidly, and the equipment fails to meet fully the present-day requirements. Limitations sometimes stem from complex logic links which can but hardly be effected by conventional means; the need for rather intricate calculations also imposes limitations. At any

rate computerization would yield certain results too insignificant often to pay back for all expenses linked with the above-mentioned measures for improving reliability of computers and organizing qualified maintenance. Therefore, the experience of using computers for solving such problems makes it possible to recommend employment of them also for the problems which can be solved without computers, but require bulky and expensive equipment.

Such a combined or system, as it is frequently called, approach to the control means permits integrated utilization of equipment including, in addition to computers, various transducers, secondary switching circuits, etc. It also opens up new possibilities for improving methods of solution of such problems. A suggested list of computerized system functions at control substations is as follows:

— logging of events;

— control of auxiliary equipment;

— monitoring of transformer temperature, calculation of permissible overloads;

— preparation of switch procedures, check of proper operation sequence;

— calculation of distance to breakdown point at employment of pulse or other measuring means;

— control of communication equipment (in particular, changeover to stand-by equipment or stand-by power source);

— participation in telecontrol system operation (scanning of transducers, supply of serial codes);

— recording of continuous information (instead of or jointly with breakdown oscillographs);

— accomplishment of logic part functions of relay protection, line and emergency control automatics.

Calculations reveal that one system with an improved reliability computer is approximately equal in cost to 150 panels with relay equipment. Approximately such a number of panels is being presently installed at large substations, therefore improving reliability of computers and system approach to them are quite reasonable.

Reliable and cheap microcomputers which have recently appeared allow creation of decentralized (distributed) systems where each machine performs a limited number of functions thus offering a more customary approach to power industry problems.

REVIEW QUESTIONS

1. What are the differences between the DC systems of countries with nationalized and non-nationalized power industries?
2. What is a general structure of computing means in the power system automated DC?
3. What are the main problems solved by the operating-information and computing complexes of the power system ADCS?

4. What are the speed of operation and volume of main memory characteristic of the RTCS and CC hardware?
5. What are the comparative requirements for speed of operation imposed by different ADCS problems?
6. What are the comparative requirements for hardware reliability to be met by the RTCS and CC?
7. What structures of the equipment are characteristic to-day of the power system ADCS?
8. Are the collective-use computing systems eployed in power industry? Outline the peculiarity of such a use.
9. What are the functions of computers installed presently at power stations? What is the volume of information handled by such machines and what is the preferred structure for them?
10. What are the functions of computers installed presently at substations? What is the difference between the centralized protection and automatic computerized equipment and conventional decentralized embodiment of such devices? What are the types of computer presently used at substations?

Chapter 5

Collection and Transmission of Information in ADCS

5.1. Communication Channels. General

Optimal supervision and control of the functioning of any major power system implies that all its power installations (electric power stations, sub-stations, dispatch control centers of various hierarchy levels, etc.) be integrated under an Automated Dispatch Control System (ADCS) through appropriate information transmission facilities. Together with associated communication channels, these facilities must be united into a whole system of communications ensuring a reliable and undistorted transmission and reception of all and any information essential to a successful functioning of the ADCS.

As power systems grow larger and more difficult to manage and control, the techniques and means of information transmission and reception are undergoing continuous changes towards higher sophistication. At present, a wide range of facilities are employed in power industry for transmission of information between power installations and dispatch control centers of power systems and groups thereof. These include telephone, teletype and short-haul single-channel telemetering equipment, single-channel pulse-code modulation (PCM) telemetering equipment, and multi-purpose multi-channel PCM telecontrol equipment. However, only the PCM equipment and the more recent data transmission systems (DTS) can meet the ADCS standards for a fast, accurate, reliable and truthful transmission of all requisite types of data through a minimum of communication channels and material. It is precisely for this reason that our further discussion will focus mainly on these data transmission facilities and communication channels they employ.

Communication channels. In power industry, information can be transmitted over wire and radio links. Under the current project of the USSR United Automatic Communications System (UACS), the principal communications link used will be two-way voice-band (VB) duplex channel with a baseband of 300 to 3 400 Hz, commonly known as the telephone channel.

All telephone channels of a given direction will be grouped into trunks by means of RF or microwave multiplexing equipment linking appropriate communication centers. Long-haul data transmission capability will be ensured by interposing chains of the so-called via, or through, RF amplifiers (in the case of wire communications) or radio-relay stations (in the case of microwave communications) into the trunks. Stations linking the communication channels with the sources and users of information are called *terminal stations*, or *final terminals*. Stations providing a link between the line trunks are known as *repeaters*, and stations performing both these functions are termed *transmit-receive stations*. The communication channel linking the source of information and its user on a permanent basis is called *private*, or *non-switched*. Conversely, a channel will be referred to as *switched* whenever some kind of circuit switching is required to establish a contact between users. Both switched and non-switched channels are finding extensive application in the power industry. Thus, non-switched channels are employed in protective relay systems, emergency control schemes, and for transmission of telemetering and telecontrol information to dispatch control centers. Switched channels are utilized for telephone, telegraph and teletype communications, as well as for organizing data transmission systems.

Wire communication links are classed into overhead and buried (cable) links. The former employ a two-wire, two-band information transmission scheme, whereby transmission in either direction requires the use of two physical wires, with the traffic of one direction proceeding within a frequency spectrum from f_1 to f_2 and that of the opposite direction occupying a range of frequencies from f_3 to f_4. Separation of these basebands in the terminal and through stations is by means of special filters which so segregate the two spectra as to ensure an unhampered transmission of information in opposite directions. In contradistinction to that, cable links normally rely on a four-wire, one-pole transmission arrangement, whereby the traffics of opposite directions are carried by separate cable pairs but occupy one and the same spectrum of frequencies from f_1 to f_2.

Overhead lines are less reliable, and are characterized by a smaller crosstalk attenuation between adjacent circuits. Because of this, the simpler and more economical one-band four-wire communication system becomes impractical with overhead lines. Further, the sharply varying degree of signal attenuation in the overhead lines necessitates the use of complex automatic gain control (AGC) systems, while the need to employ the two-band transmission arrangement forces the designers to site repeaters much more closely and reduces the number of transmission channels. Finally, overhead lines are much more susceptible to the adverse effects of neighboring

communication links, power transmission lines and contact systems. Because of these reasons, cable data transmission systems are considered to be preferable in power industry. But, use is still widely made of the so-called power line carrier communications implemented by means of special RF multiplexing equipment that allows up to 12 telephone channels to be organized within a frequency range of up to 500 kHz.

Radio communications is used primarily within dispatch control centers of district and utility levels as a means of managing repair teams. But in a number of instances radio communications is utilized to provide a back-up support for wire dispatch control services between the dispatch control centers of individual power systems and groups thereof, the USSR United Power Grid Central Control Department (UPG CCD) and major power installations and consumers. In all such instances, radio relay communications are predominant.

In power industry, both nation-wide and organizational-level communication channels are used extensively. Indeed, an Automated Dispatch Control System would hardly be successful unless provisions are made to transmit, receive and otherwise handle large volumes of operational, production, statistical and managerial information. This calls for the construction of a developed network of organizational-level cable systems capable of providing non-switched communications services.

The structure of communication channels in power industry follows the hierarchy of dispatch and management control, at the top of which are the UPG CCD, area-level control boards and dispatch control centers of individual power systems. All dispatch control centers and major power stations and sub-stations are equipped with their own communication centers. At the heart of each such center is a control room housing wire- and radio-link multiplexing equipment and VB-channel sub-multiplexing equipment providing the teletype, telecontrol and data transmission services.

The basic functions of the control room equipment, apart from multiplexing, consist in accomplishing through connections between various communication channels, testing of these channels, and routing them to the switchboard, telephone, phototelegraph, telecontrol and data transmission rooms as appropriate.

Multiplexing equipment. Multiplexing equipment serves to obtain several communication channels within the frequency spectra of the wire and radio links. Two major channel multiplexing principles are identified. These are known as frequency division multiplex (FDM) and time division multiplex (TDM). With FDM, the signals of each individual channel are transmitted within a separate frequency band of the link overall frequency spectrum. Time division multiplex consists in that the entire link is successively connected to the information sources and respective users, so that each user

stays connected with his source only for a limited amount of time. One of the most commonly used types of multiplexing equipment is the one accomplishing frequency division of communication links into VB channels of equal basebands (from 300 to 3 400 Hz).

In most cases, the FDM equipment employs amplitude modulation (AM), single-sideband (SSB) transmission technique as the one requiring a minimum frequency spectrum per VB channel. With other multiplex techniques, frequency occupation is much wider. For instance, with TDM equipment, a frequency spectrum is 15 to 20 times as wide as with FDM.

To convert equal basebands of the standard telephone (VB) channels into their respective RF links without altering the original amplitude and frequency relationships (i.e., without changing the baseband width, the number of frequency components making up the signal spectrum, and their amplitudes), each such channel is equipped with it own *modulator*. If a signal with a frequency spectrum from F_{LSB} to F_{USB} is applied to the modulator whose carrier frequency is f_c, the output will be two useful sidebands with a spectrum from $f_c - F_{USB}$ to $f_c + F_{USB}$, or $2F_{USB}$.

The re-conversion from the RF spectrum into the VB spectrum (from F_{LSB} to F_{USB}) is accomplished by *demodulators*. Each demodulator accepts one or both sidebands and the carrier, and puts out a signal spectrum that, in terms of frequency and amplitude, is identical to the one originally applied to the modulator input.

Apart from the useful frequency spectra (sidebands $f_c \pm F_{USB}$), modulation results in unwanted (spurious) frequencies lying beyond the spectra of the useful signals, for example $2f_c \pm F$, $3f_c \pm F$, etc. Similarly, the process of demodulation yields unwanted frequencies f_c, $2f_c$, $2(f_c \pm F)$. To reject these, use has to be made of special filters interposed at the rear ends of modulators and demodulators.

In multiplexing equipment, the modulator of each channel has a unique carrier frequency (f_{c1}, f_{c2}, . . ., f_{cn}, with 1, 2, . . ., n being the channel number). As a result, the sidebands of each individual channel occupy different positions within the link overall frequency band. At the receiving end of the link, these sidebands are segregated into respective frequency bands with the help of bandpass separation filters at the front ends of demodulators of appropriate channels.

In order that twice as many channels could be squeezed into the communication link frequency spectrum, the carrier of each individual channel and one of its sidebands are suppressed. The inevitable loss of the useful signal power is made up for by raising the receiving equipment gain. Carrier f_c needed to effect signal demodulation is supplied locally (hence the name local oscillator). Such a technique is known as *suppressed-carrier single-sideband* (SSB) transmission,

and is widely used for channel multiplexing in long-haul communications.

Modulators and demodulators have much in common, both schematically and functionally, for they serve to convert signals from one frequency spectrum to another without altering the original amplitude and frequency relationships of these signals. The only difference between modulators and demodulators is that the former convert voice-band signals into radio-frequency signals, whereas the latter do the opposite. To stress this functional and schematic similarity, in long-haul communications engineering, the modulators and demodulators are commonly called *frequency converters*, with the words send or receive added when necessary to provide a distinction.

Accepted as the basic primary channel group is a group of 12 channels occupying a spectrum of frequencies from 60 to 108 kHz, with each channel being 4-kHz wide (60 to 64 kHz, 64 to 68 kHz, . . ., 104 to 108 kHz).

At the send end of the link, the 12 different sidebands are obtained, shaped and separated (Fig. 5.1) by individual send converters SC1 through SC12 each of which is provided with its own carrier frequency oscillator (CFO1 through CFO12) of a unique carrier (64, 68, . . ., 108 kHz). At the rear end of each frequency converter there is a special bandpass filter (BPF1 through BPF12) that rejects the upper sideband resulting from frequency conversion. The thus obtained spectrum of the 12-channel group is then routed to a group converter whose function is to convert it into the spectrum transmitted over the multiplexed link.

At the receiving end of the link, the conversion process is reversed. The incoming signal is routed to a group converter which discriminates a spectrum of frequencies between 60.6 and 107.3 kHz. With the aid of appropriate bandpass filters and demodulators (receive converters), this spectrum is then separated into 12 VB channels, with the necessary carrier frequencies supplied to the demodulators by their respective local oscillators.

The desire to reduce the number of requisite communication channels has led to the development of the so-called sub-multiplexing of telephone (VB) channels—a technique widely made use of in power industry communications. The equipment designed to convert the original signal frequencies into the VB channel frequency spectrum (at the send end) and, conversely, the VB channel frequency spectrum into the original spectrum of frequencies (at the receive end) is called the *communication link sub-multiplexing equipment* (SME).

Various types of SME have been developed to provide a diversity of communication services, such as simultaneous telephony, telegraphy and phototelegraphy, simultaneous telephony and tele-

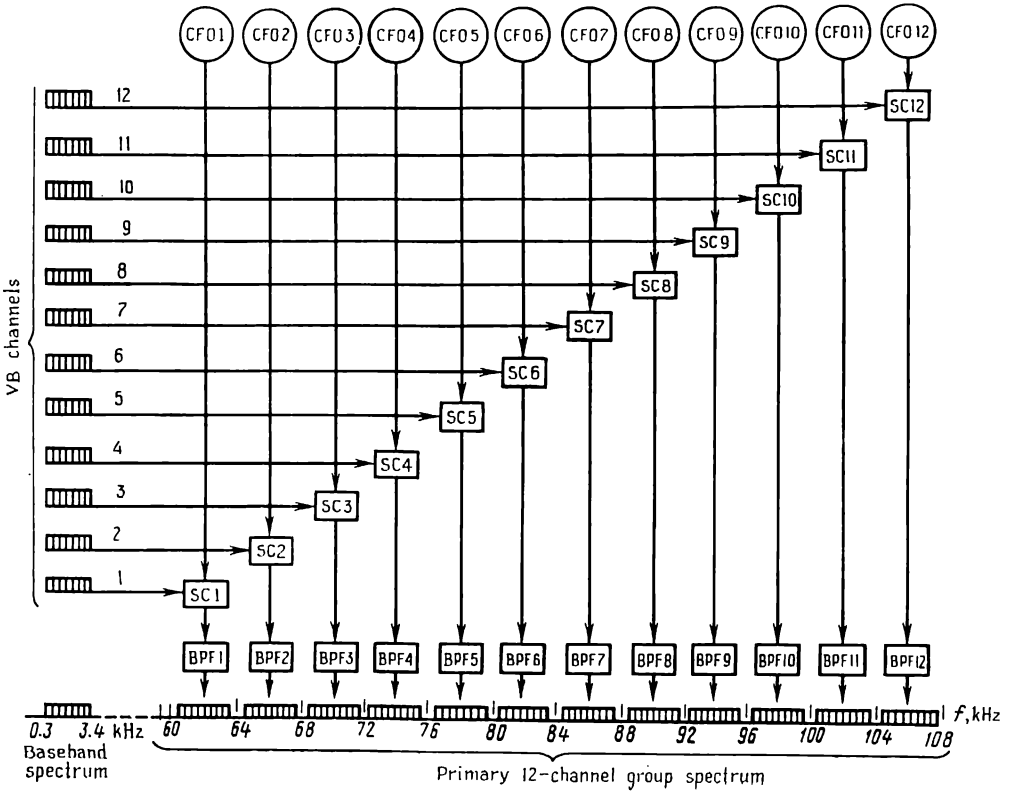

CFO1
CFO2
CFO3
CFO4
CFO5
CFO6
CFO7
CFO8
CFO9
CFO10
CFO11
CFO12
VB channels
12
11
10
9
8
7
6
5
4
3
2
1
SC12
SC11
SC10
SC9
SC8
SC7
SC6
SC5
SC4
SC3
SC2
SC1
BPF1
BPF2
BPF3
BPF4
BPF5
BPF6
BPF7
BPF8
BPF9
BPF10
BPF11
BPF12
0.3 3.4 kHz
Baseband spectrum
60 64 68 72 76 80 84 88 92 96 100 104 108
f, kHz
Primary 12-channel group spectrum

Fig. 5.1

metering, voice-frequency carrier telegraphy and transmission of alphanumeric information through data transmission systems, etc. Sub-multiplexing of existing communication channels allows the range of communications to be increased, and requires no special through amplifiers because the SME signals are handled by the multiplexing equipment amplifiers just as easily as those of other communication channels. Accordingly, a SME system has only terminal stations and no repeaters. In power industry, one of the most extensively used sub-multiplexing systems is the one that allows organization, within a single VB channel, of one engineering telephone channel with a frequency spectrum of 300 to 2 400 Hz plus one or several auxiliary channels with a spectrum from 2 400 to 3 400 Hz. The number and spectrum of each of these channels is conditioned by the modulation technique employed and the speed characteristics of the devices served by the SME at the send and receive ends of a given link.

Transmission of discrete information. The majority of parameters characterizing the functioning and state of power systems are varying continuously in the time domain. Examples of such parameters are the load active and reactive powers, load flows over the power lines, voltage and frequency, generation and consumption of electric energy, consumption of fuel, water, etc. Accurate and truthful transmission of their values over long distances is hardly feasible unless these parameters are represented in a discrete form.

For transmission over a VB channel, the original spectrum of the discrete signal is translated into that channel frequency spectrum by means of modems (an acronym for modulator/demodulator) of various types. These can be AM modems, in which the carrier is amplitude-modulated from zero to a certain maximum; FM modems, in which the carrier is frequency modulated so that it changes from f_1 to f_2, and conversely; PM modems, in which the carrier is phase-modulated to vary between 0° and 180° or between 0°-180° and 90°-270° (depending on the keying technique used).

In most types of SME, double-sideband transmission is employed, with the carrier of the modulated signal positioned in the center of the spectrum of the sub-multiplexed channel. SSB sub-multiplexing was found to be inacceptable because of prohibitive signal distortions.

The simplified circuits for AM, FM and PM transmission of discrete signals are illustrated in Fig. 5.2. The respective modulators are shown to accept two-pole on-off keyed signals of the type used in telegraphy. Depending on the modulation technique employed, the modulators put out double-sideband signals centered around a respective carrier. The signal waveforms for the various modulation techniques are depicted over the communication channel lines (dotted). In all three schemes, the modulated signals are boosted by a send

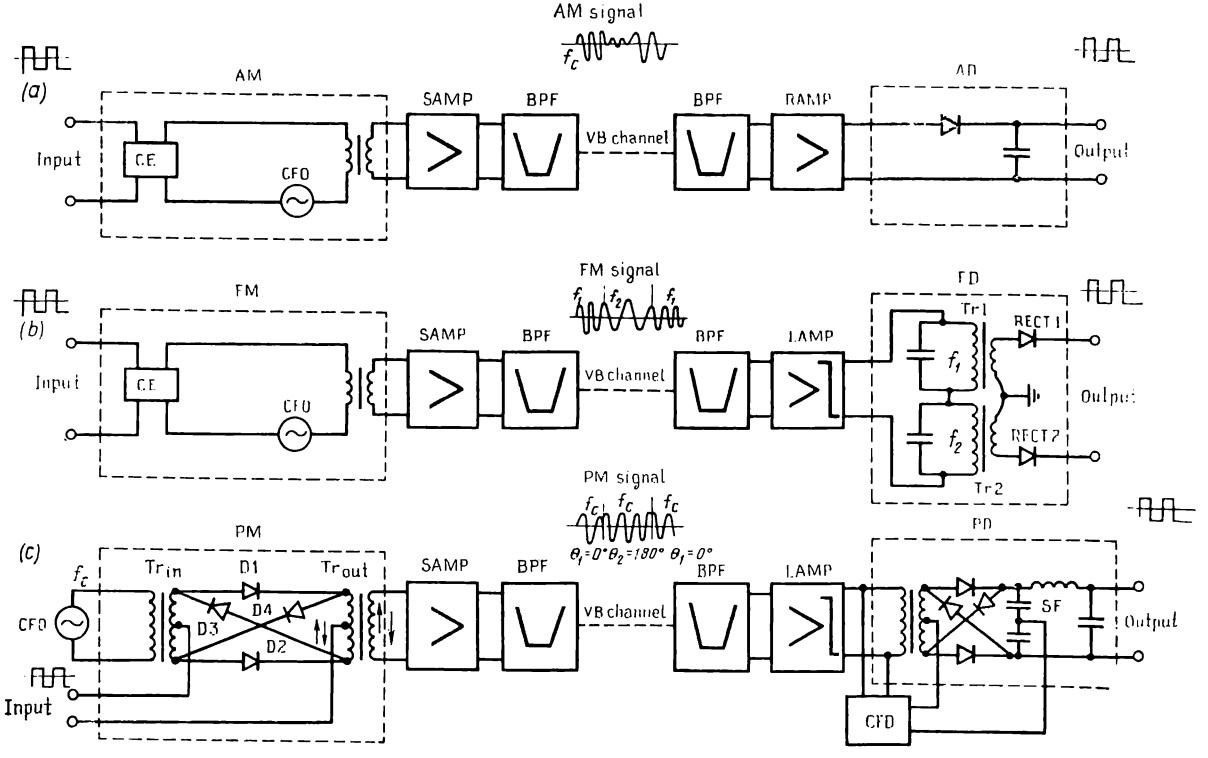

AM signal
(a)
AM
Input
C.E
CFO
SAMP
BPF
VB channel
BPF
RAMP
AD
Output
FM signal
(b)
FM
Input
C.E
CFO
SAMP
BPF
VB channel
BPF
LAMP
FD
Tr1
RECT1
RECT2
Tr2
Output
PM signal
$\theta_1=0°\ \theta_2=180°\ \theta_1=0°$
(c)
PM
f_c
CFO
Input
Tr_{in}
D1
Tr_{out}
D4
D3
D2
SAMP
BPF
VB channel
BPF
LAMP
PD
SF
CFD
Output

Fig. 5.2

amplifier and passed through a bandpass filter (BPF) which restricts the sidebands of the modulated signals to the first harmonic of the maximum frequency of the original modulating signal, F_{max}, such that $\Delta f \approx 2F_{max}$. The signals are next sent over the VB channel to a receiver that reproduces the waveform of the discrete signals applied to the modulator.

Amplitude-modulated signals are transmitted as shown in (*a*) of Fig. 5.2. The input pulses are applied to the control element (CE) of the amplitude modulator (AM). The functions of the control element can be performed by vacuum tubes, transistors, controlled rectifiers or relays. Following the input pulse amplitude, the CE amplifies or attenuates the carrier frequency oscillator (CFO) signals. Boosted by the send amplifier, the AM signals are sent through the bandpass filter over the VB channel. At the other end of the channel, the AM signals are routed through the receive station BPF (which filters out noise and signals from other channels) to the receive amplifier (RAMP). The amplifier output goes to the amplitude demodulator (AD) which rectifies and smooths the modulated signals, thereby discriminating their envelop—a fairly truthful reproduction of the signals applied to the AM.

Transmission of frequency modulated signals proceeds as shown in (*b*) of Fig. 5.2. Here, the input pulses are applied to the frequency modulator (FM) via its control element (CE). Used in the capacity of the control element can be varicaps or any other devices that exhibit dependency of their reactance upon the modulating signal. As a result, the frequency of the CFO oscillatory circuit will follow the amplitude of the input pulses, varying between f_1 and f_2, whereas the CFO signal amplitude will remain constant.

Through the send amplifier (SAMP) and bandpass filter (BPF), the FM signals are carried over the communication channel into the limiting amplifier (LAMP), which maintains the signal at a substantially constant level and clips off the amplitude spikes that might have been superimposed upon the useful signal in the communication channel by noise. The LAMP thus improves the transmitted information noise immunity. Its output is coupled to the frequency demodulator (FD), or discriminator. The latter is made up of two oscillatory circuits tuned to frequencies f_1 and f_2. The currents of each of these frequencies then go via transformers TR1 and TR2 to respective rectifiers RECT1 and RECT2 whose outputs closely follow the waveforms of the signals originally fed to the FM.

Finally, Fig. 5.2 (*c*) shows the circuit for transmission of discrete signals over a phase-modulated communication channel. At the front end of this particular scheme there is a phase modulator (PM) of the balanced ring variety made up of four diodes (D1 through D4) connected back-to-back in pairs. The signals of carrier frequency

(f_c) are split in the secondary of input transformer TR_{in} and pass through the primary of output transformer TR_{out} in opposite directions. Consequently, the f_c signal is available from the secondary of TR_{out} only as long as there are pulses applied to the phase modulator.

With positive-polarity information-carrying signals applied to the center taps of the PM circuit, the resistance of diodes D1 and D2 drops, while that of diodes D3 and D4 rises. This upsets the balance of carrier currents through the primary of TR_{out}, and a signal of phase $\Theta = 0°$ appears in its secondary. If now the polarity of the input signal is reversed, the resistance of diodes D1 and D2 will rise, whereas that of diodes D3 and D4 will drop, with the result that the phase of the current through the output transformer will change by 180°. The resultant phase-modulated signal is sent through the send amplifier and bandpass filter to the VB channel. At the receiving end of the channel, the signal goes via the bandpass filter and limiting amplifier to the phase demodulator (PD). The synchronous carrier, f_c, is then discriminated from the PM signal by a special carrier frequency discriminator (CFD).

If the PM signal currents are phase-coincident with the carrier frequency currents, the output of the PD will be positive halfwaves of current. Smoothed by the smoothing filter (SF), these signals will fairly closely follow the waveform of the PM positive pulses. If the PM signal currents are not in-phase with the carrier frequency currents, the current out of the PD circuit will reverse, and the signals out of the SF will repeat the negative pulses applied to the PM.

Comparative analysis of the various modulation techniques can be attempted through application of certain specific criteria (for there exists no commonly accepted general criterion that would help assess the pros and cons of the various methods of discrete signal transmission). Taken as such criteria can, for example, be the communication channel noise immunity and stability of its characteristics, the requisite frequency band, and complexity of the equipment used.

Noise immunity exhibits a heavy dependence on the modulation technique used. Thus, amplitude modulation is the least immune to noise, because the latter may well impregnate the receiver during the resting time between successive AM pulses and be accepted as a useful signal. Similarly, erroneous signals can be produced by sharp variations of the received signal level. For instance, the probability of an erroneous reception of one out of 10 000 transmitted symbols ($p \leqslant 10^{-4}$) can hardly be attained unless the amplitude of the useful signal, U_s, is four to five times as high as that of noise ($U_{\bar{n}}$). Compared with AM, frequency modulation is roughly twice as immune to noise. But best immune are phase-modulated signals,

with which adequate error probability levels ($p \leqslant 10^{-4}$) are feasible at signal-to-noise ratios of $U_s/U_n \geqslant 1.5$.

The noise immunity of FM and PM channels tends to degrade sharply whenever the carrier frequencies of the multiplexing equipment send and receive converters drift apart by more than ± 3 Hz. In phase-modulated systems, additional errors result from sudden jumps of the signal phase by a value in access of $\pm 10°$. Amplitude-modulated signals are just as susceptible to sudden variations of the signal level at the receiving end of the communication channel.

Noise immunity of a FM channel can be improved somewhat by making its frequency spectrum twice or thrice as wide as normal. This technique is often employed in noisy environments for those radio links in which the widening of the transmitted signal frequency band can be tolerated.

Instability of a communication channel characteristics is in most cases due to short-term open circuits likely to exist in all types of channels whose through connections are made by decade step-by-step selector switches. Short-term open circuits may also exist due to poor bank-and-wiper action or vibration of connecting cords. The adverse effects of the open circuits are essentially the same for all types of modulation.

The band of frequencies required for the transmission of modulated signals is contingent with such factors as the modulation rate, admissible level of phase distortions, presence of low frequencies and DC component within the spectrum of the input signals, number of sidebands transmitted, etc.

For the signal low-frequency and DC components to be transmitted, both sidebands of the modulated carrier have to be transmitted, so that $\Delta f = 2F_{max} = B$, with being the keying speed in bauds. Different frequencies of the transmitted spectrum are retarded differently (which gives rise to phase distortions), this makes it imperative to have the frequency band required to transmit the modulated signals stretched to (1.25-1.6) B. Bandpass filters retard most heavily the spectrum components lying in the vicinity of their cutoff frequencies. To counter this effect, special phase equalizing circuits are interposed in series with bandpass filters in order that the basic components of the signal spectrum would experience an approximately equal retardation. In this way, either the requisite bandwidth of the communication channel can be reduced to 1.1 B, or the keying speed can be increased by a factor of 1.3 to 1.5.

As far as **complexity** of the communication equipment is concerned, amplitude modulation offers greatest advantages, because demodulation of AM signals at the receiving end of the link necessitates no restoration of the carrier. Besides, AM equipment is immune to frequency variations in the communication channel.

Of medium complexity turns out to be FM equipment, which

can operate reliably at U_s/U_n ratios of 2.5 or better. This prompted the CCITT to recommend the use of medium-speed FM sub-multiplexing equipment for transmission of information over telephone-grade (VB) channels.

Most complex of all is PM equipment. In noisy environments ($U_s/U_n \geqslant 1.5$-2.0), data transmission systems employing single-cycle phase modulation are considered preferable. On the other hand, push-pull phase modulation equipment allows the information handling capacity of the communication channel to be doubled by having one extra information flow transmitted independently on a carrier shifted through 90° with respect to the first channel carrier. The noise immunity of such a link is the same as in the case of FM. At keying speeds exceeding 1 200 bauds, push-pull phase modulation equipment is more economical.

In low-noise communication channels ($U_s/U_n > 10$) characterized by moderate variations of the signal level at the receiving end (± 0.4 nepers maximum), any of the modulation methods discussed above ensures an equally small number of reception errors. Under such conditions, the simpler AM equipment, immune to the divergence of frequencies at the VB channel transmit and receive ends offers greater advantages.

5.2. Multichannel Pulse-Coded Modulation Telecontrol Devices

Most of the parameters characterizing the functioning and state of a power system tend to vary continuously in the time domain. Among these parameters, are the active and reactive loads, active and reactive power flows between intersystem nets, voltage and frequency at certain points of the grid, generation and consumption of the electrical energy, consumption of fuel, expenditure of water, etc.

For transmission of information as a continuous function of time, $F(t)$, every secondary device (indicator) must be permanently linked with the respective primary device (transducer), so that the two would form the so-called single-channel system. Information is transmitted over cable or power-line carrier (PLC) communication links. To ensure a better efficiency of these links, resort is had to the so-called frequency-division multiplex technique, which consists in that the entire frequency spectrum of a given link, f_l, is divided into a number of non-overlapping frequency bands (Δf_1, Δf_2, Δf_3, . . ., Δf_n) each of which is then treated as a separate communication channel.

Thus, a one-link continuous (analog) information transmission system can be employed for telemetering of several quantities. The number of such channels is relatively small, while the per-

channel equipment and maintenance costs turn out to be rather high. Besides, no formalized methods for checking the information validity have so far been developed for the continuous transmission systems. Indeed, with noise present within the frequency band of a given channel there is no other way to check for the validity of the transmitted information (without divulging into its contents) except through the use of two parallel channels of different frequencies.

Thus, accurate, truthful and reliable transmission of information over long distances is hardly possible unless it is digitized. In a discrete system, the expedient rate of transmission of parameters, as well as their quantizing and sampling periods, are conditioned primarily by requisite waveform reproduction accuracy at the receiving end. Digitization of a continuous (analog) function means that the original function is represented by a sequence of samples taken at equal time intervals, known as *sampling period*, T_0.

The reciprocal of the sampling period is known as *sampling rate*. According to the Kotelnikov theorem, the sampling rate must equal at least twice the maximum frequency of the sampled function spectrum, although it should be stressed that this theorem applies only to functions of a limited spectrum transmitted in fairly wide pulses other than those of delta functions.

At any finite sampling rate, there is always a pause between two successive samples of a function. The duration of that pause equals the sampling period less the time needed to take one sample and transmit it over the communication channel. A way thus opens for transmitting the values of other functions during the pause—an arrangement that effectively means submultiplexing the existing communication channels through application of the time-division multiplex principle. In practical terms, time-division multiplex implies that all information sources are successively sampled (polled) at the transmit end, and the samples from each individual source are somehow stored at the receive end of the communication link. For this reason, multichannel telecontrol systems rely mostly on the pulse-coded modulation (PCM) principle which permits representation of function values as successions of binary signals that can be fairly easily stored at the receive end in standard memory units of the type widely used in computers.

Types of teleinformation. Multichannel PCM telecontrol systems are capable of transmitting a variety of information types. In these systems, information is transmitted in the form of individual messages (words) containing an equal number of binary digits. Therefore the type of a given teleinformation is determined first and foremost by the source, direction of transmission and destination of each particular message. Accordingly, information transmission can be classed into several types, the basic of which are as follows:

— telemetering (TM), implying transmission of such instantaneous measurands as power, current, frequency, voltage, etc.;
— teleindication (TI), implying transmission of information indicative of the state of two-state devices, such as switches, circuit breakers, etc.;
— telecommand (TC), implying transmission of commands of the ON-OFF type;
— blocking telecommand (BTC), implying transmission of commands blocking the action of protective relay equipment and such like devices;
— teleregulation (TR), implying transmission of commands of the HIGHER-LOWER or INCREASE-DECREASE type;
— telemetering on demand (TOD), implying transmission of one or more measurands on demand.

Also, multichannel PCM telecontrol systems are adaptable for transmission of alphanumeric symbols and characters (commonly referred to as statistical information, or SI). In dispatch and supervisory control, multichannel PCM telecontrol systems are used primarily for transmission of TM and TI information.

Information can be transmitted cyclically, spontaneously, or on demand.

Cyclic transmission is most frequently used with TM information. The term cyclic denotes that code combinations (words) corresponding to the instantaneous (current) values of the telemetered measurands are generated and sent over the communication channel on a cyclic basis. The time interval between transmission of two successive values of one and the same measurand (known as the updating, or refreshment, time) is conditioned by the number of measurands to be transmitted and the time needed to transmit each of them.

Spontaneous transmission is a transmission method where messages are transmitted only when an event occurs at the sending station. Most frequently, spontaneous transmission is applied to TI, BTC, TC, SI and TR messages, with TC, TR, BTC and SI messages transmitted as they occur, and TI messages transmitted only when the state of at least one of the monitored stations changes.

It is important to stress at this point that spontaneous transmission scheme will hardly be practical unless there is a return communication channel provided to carry, from the receiver to originator, an acknowledgement of a correct reception of the transmitted messages. Also, with spontaneous transmission a need often arises in having simultaneously occurring messages arranged in a queue, so that they all could be transmitted in an orderly fashion. Usually, the messages are ordered on the basis of their *priority*. The priority of each type of information is determined by its significance in

control of a given power system. Thus, the above-mentioned types of information are usually lined up in the increasing order of their priority as SI, TOD, TM, TI, TR, TC and BTC.

Transmitted on demand from the receiving end can be the messages of the SI, TOD and TI types. The receiving station then generates a request in which the types and specific list of the requisite information are explicitly stated. This request is sent over the return channel to the send station and is treated by its transmitter as a command requiring an immediate response action. Upon this command, the cyclic transmission of routine messages is discontinued, and the transmission of the demanded messages is initiated instead.

Two arrangements for the transmission of on-demand messages are possible. In one, the transmission of all other types of information (except those of a higher priority) is discontinued for as long as the demanded messages are being transmitted (or until the receiving station sends in a command cancelling the cyclic transmission of these messages). In the other, the demanded messages are transmitted cyclically in queue with the routine types of information without causing a break in their transmission.

A multichannel PCM telecontrol system normally consists of one transmit and one or more receive subsets. The transmit subset for TM is sited with the controlled station (also called the remote station, or outstation), abbreviated CS. This can be an electric power station, a substation, a subordinate dispatch control center, etc. The receive subset is sited with the master station (MS)—a dispatch control center higher in the system hierarchy.

In Soviet power industry, the most widely used multichannel PCM telecontrol systems are the MKT-1, MKT-2, STIMUL, TM-511, TM-512 and KUST systems employing register-type storage devices. The number of these storage registers (SR) is contingent with the number of transmitted measurands, which means that an individual storage register is provided for each single measurand being transmitted. All storage registers can accommodate an equal number of binary digits regardless of the type or numerical value of the message stored.

Transducers. Every message must be coded at the transmit end and decoded at the receive end. Coding pursues a dual function of (a) bringing the transmitted message to the standard word length employed in a given system, and (b) translating the message into a most noise-immune format ensuring a reliable and accurate transmission over a noisy channel. As regards such types of information as TM and TOD, the former function is normally performed through the use of special transducers putting out a normalized signal.

Used most extensively are transducers converting the measurand into a DC signal varying between 0 and ± 5 mA.

Normally, the real transducer signal, $y(t)$, differs from the measurand, $x(t)$, both in amplitude and phase—a phenomenon giving rise to the so-called conversion (transducer) error. The spectral density of the output function, $y(t)$, equals that of the measured function, $x(t)$, times the modulus of the transmitter frequency characteristic, $\Phi(j\omega)$, squared

$$S_y(\omega) = S_x(\omega)\,|\Phi(j\omega)|^2$$

For transducers converting the measurand variations into mechanical displacement of the coding element, account must additionally be made of the moving mechanism response time. The frequency characteristic of a majority of such transducers has the following form:

$$\Phi_{tr}(j\omega) = (1 + j\omega T_{tr})^{-1}$$

where T_{tr} is the transducer time constant.

The transducers whose output signal takes the form of a direct current are commonly classed into two basic groups:

— transducers generating the output signal directly (examples are thermocouples, piezoelectric pickups, etc.) or with the aid of DC measuring circuits;

— transducers whose output DC signal is the result of rectifications of AC signals.

Application of transducers of the first group requires that an account be made of their response time (time constant), which in some cases may even exceed that of purely mechanical transducers.

Transducers of the second group are characterized by conversion errors caused by the output current ripples. The latter can be reduced though by means of special smoothing filters. The magnitude of the ripple-caused errors will then be in reverse proportion to the filter time constant, T_F. It must be remembered, however, that a large T_F is equivalent to a small cutoff frequency, ω_c, and eventually means a degradation of the filter capacity to handle signals.

The square of the root-mean-square error introduced by the filter is given by

$$\delta^2_{F,\,\mathrm{rms}} = \delta^2_{n,\,\mathrm{rms}} + \delta^2_{N,\,\mathrm{rms}}$$

where $\delta^2_{n,rms} = S_x(\omega)\,|\,1 - \Phi_F(j\omega)\,|^2$ is the square of the root-mean-square error due to non-ideal transfer of the controlled process spectrum by a filter of frequency characteristic $\Phi_F(j\omega)$;

$\delta^2_{N,rms} = S_N(\omega_N)\,|\,\Phi_F(j\omega)\,|^2$ is the square of the root-mean-square error due to the filter output ripples, conditioned by spectral density $S_N(\omega_N)$ of the noise caused by the transducer supply voltage ripples of frequency ω_N and the filter frequency characteristic $\Phi_F(j\omega)$.

Analog-to-digital converters. As its name implies, an analog-to-digital (A/D) converter is a device designed to digitize an analog waveform by quantizing each of its instantaneous values to the nearest standard value known as quantization level, or subrange. The quantization error of a telemetered quantity is determined by the number of the A/D converter digits and the code (number system) in which the quantized value is represented.

If each message contains a total of n binary digits and the discrete values of the measurand are represented in a code with base a, then the maximum quantizing error will be expressed as

$$\delta_{q\,\max} = \pm [2^{(n-lm+1)}a^l]^{-1}$$

where $l \leqslant n/m$ is a whole number showing how many times the base can be written in a single word containing n binary digits; m is the number of binary digits needed to express the base of the given system.

For example, in Soviet-made STIMUL-2M telecontrol systems, TM information is transmitted in binary-coded-decimal (BCD) words of nine binary digits each, and the maximum quantizing error constitutes

$$\delta_{q\,\max} = \pm [2^{(9-2\times4+1)} \times 10^2]^{-1} = 2.5 \times 10^{-3}$$

If a purely binary notation (code) were used, the maximum quantizing error would be given by

$$\delta_{q\,\max} = 2^{-(n+1)}$$

With the quantizing error distributed uniformly, the root-mean-square quantizing error is given by

$$\delta_{q\,\mathrm{rms}} = \delta_{q\,\max}/\sqrt{3}$$

or $\sqrt{3}$ times as small as the maximum error.

Sampling (time quantization) of a continuous function inevitably results in a partial loss of information on that function. This gives rise to the so-called sampling error, whose magnitude is dependent on both the sampling period and the method used to restore the original waveform of the function at the receiving end. Various methods exist by which function $x\,(t)$ can be interpolated by its known samples $x\,(t_i)$ taken at certain sampling points (nodes of interpolation).

At the nodes of interpolation, interpolating function $y\,(t)$ assumes the same values as function $x\,(t)$

$$y\,(t_0) = x\,(t_0),\ y\,(t_1) = x\,(t_1),\ \ldots,\ y\,(t_m) = x\,(t_m).$$

In the general case, the problem reduces to finding the curve $y\,(t)$ passing through the pre-assigned system of sampling points.

The choice and practical realization of a particular interpolation method are governed by such factors as purpose of the given telemetering device, requisite interpolation accuracy, and characteristics of the telemetered process. In power industry, use is mostly made of telecontrol systems employing the step-wise interpolation principle easily realizable with the aid of storage devices capable of storing the current value $y(t_i)$ until the arrival of the next value, $y(t_{i+1})$.

With step-wise interpolation, the value of function $y(t_u)$ at the instant of observation is assumed to be equal to the previously obtained function sample $y(t_i)$. In this way, the original function is successively interpolated from one sampling point, t_i, to the next, t_{i+1} (Fig. 5.3).

The interpolation (dynamic) error, given by $\delta_{d.i} = x(t_u) - y(t_u)$, can be found from expression

$$R = \frac{x^{(n+1)}(t')}{(n+1)!} \times (t-t_0)(t-t_1)\ldots(t-t_n)$$

where t' is an arbitrary instant of time between the instants of interpolation $t_0, t_1, \ldots, t_n$ and the instant in question, t.

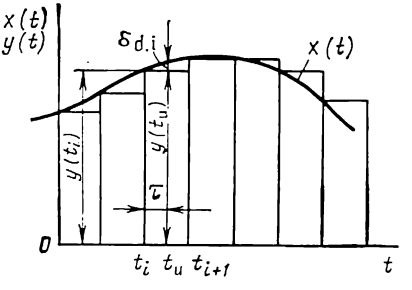


Fig. 5.3

Since in our example $n = 0$, the dynamic error will, using the notation of Fig. 5.3, be expressed as

$$\delta_{d.i} = x'(t')(t_u - t_i)$$

The interpolation error will be greatest at a maximum telemetering period $T_0 = t_{i+1} - t_i$ and a maximum magnitude of the measurand derivative obtainable within that period.

For functions of a finite cutoff frequency ω_c and modulus-bounded functions, the maximum value of the derivative can be assessed by applying the Bernstein inequality:

$$|x'(t)|_{\max} \leqslant \omega_c |x(t)|_{\max}$$

where $|x(t)|_{\max}$ is the maximum value of function $x(t)$.

Consequently, the maximum error of a step-wise interpolation will be given by

$$|\delta_{d.i}|_{\max} \leqslant \omega |x(t)|_{\max} T_0$$

The expectation (mean value) of the step-wise interpolation mean-root-square error squared equals

$$\overline{\delta^2_{d.i.}} = M\{[y(t_u) - x(t_u)]^2\}$$
$$= M[y^2(t_u)] + M[x^2(t_u)] - 2M[x(t_u)\, y(t_u)]$$

Taking into account that

$$M[x^2(t)] = M[y^2(t)]; \quad M[x(t)] = M[y(t)]$$

and

$$M[x(t_u)\, y(t_u)] = 2M[x(t_i)\, x(t_i+\tau)] = K_x(\tau)$$

the expression for $\overline{\delta}^2_{d.i}$ will take on the following form:

$$\overline{\delta}^2_{d.i} = 2D_x[1 - K_0(\tau)]$$

where D_x is the dispersion of the telemetered parameter; $K_0(\tau)$ is the normalized autocorrelation function of the telemetered parameter.

In the case of a visual monitoring of the telemetered parameter with the aid of measuring instruments, or an automatic asynchronous input of teleinformation into a digital computer,

$$\overline{\delta}^2_{d.i} = 2D_x\left[1 - \frac{1}{T_0}\int_0^{T_0} K_0(\tau)\, d\tau\right]$$

Accounting for the delay resulting from the transmission of each function sample over the communication channel (t_{tr}), the above quantity will equal

$$\overline{\delta}^2_{d.i} = 2D_x\left[1 - \frac{1}{T_0}\int_{t_{tr}}^{T_0+t_{tr}} K_0(\tau)\, d\tau\right]$$

Operation of multichannel PCM system. At the system transmit end (Fig. 5.4), the analog signals of transducers TM and TOD are converted into digital (discrete) form by a common A/D converter (ADC). The transducer signals *T1* through T_k are successively applied to the ADC by a special commutator denoted as CS FC SD (for controlled station forward channel subchannel distributor). The thus digitized signals next go from the ADC to the forward channel modulator (FCM) to be converted into a form best suited for transmission over the VB link. Used most frequently for the purpose are frequency modulators.

The master station (MS) picks up the incoming signals and sends them into the forward channel demodulator (FCD) for demodulation. Once demodulated, the signals are bit-by-bit serially routed into a common receive register (RR) from which they emerge in a parallel-code format and are fanned out by the MS FC SD (for master station, forward channel, sub-channel distributor) into appropriate storage registers (SR).

For the thus received measurands to be readable by analog meters, each storage register (SR1 through SR_k) is provided with its own

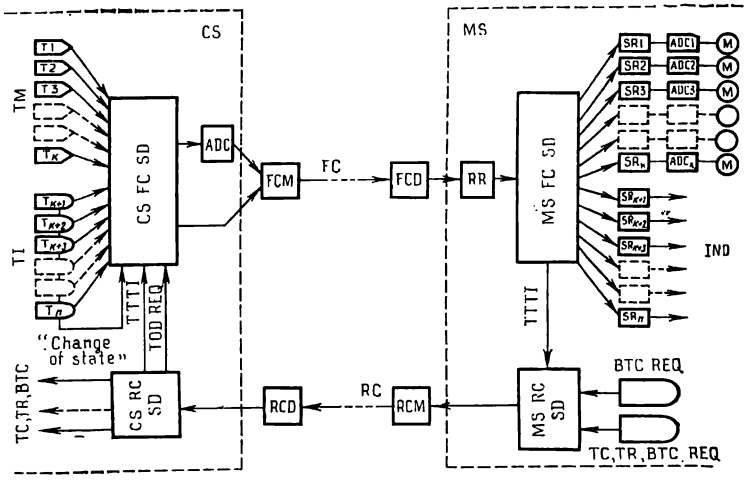


Fig. 5.4

digital-to-analog converter (DAC1 through DAC_k) to which an appropriately calibrated meter (M) can be connected.

TI transducers usually take the form of N.O. or N.C. relay contacts. Transmitted in each message is information on the current state of a group of two-state objects equal in number to the message word binary digits. TI information, it will be recalled, can be transmitted cyclically and spontaneously. Spontaneous transmission commences with the arrival of the CHANGE-OF-STATE signal, which is generated each time the state of one of the telemeterd objects undergoes a change. With the arrival of the CHANGE-OF-STATE signal, the CS FC SD distributor successively polls all the TM and TI transducers (*TI* through T_k and T_{k+1} through T_n, respectively). Since the TI messages are grouped into individual words each of which contains information on the state of n two-state objects, they by-pass the ADC and arrive directly into the FCM.

At the receive end, these messages are fanned out by the MS FC SD distributor to associated storage registers (SR_{k+1} through SR_n), wherefrom the information on the state of the telemetered two-state objects goes to the control coils of annunciator relays or some other indicators (IND). As a rule, TM and TI messages continue to be transmitted for several transmission cycles until the MS FC SD generates the TTTI (for terminate transmission of *TI*) signal. The latter goes through the MS RC SD (for master station return channel sub-channel distributor) and return channel modulator (RCM) into the return channel (RC). In the controlled station, the TTTI signal

is demodulated by the return channel demodulator (RCD) and routed to the controlled station return channel sub-channel distributor (CS RC SD). The CS RC SD uses this signal to generate the TTTI command in response to which the CS FC SD terminates the cyclic transmission of TM and TI information and organizes a cyclic transmission of the TM information only.

If a telemetering-on-demand (TOD) request (TOD REQ) arrives from the master station (MS), the CS FC SD organizes a cyclic polling of appropriate transducers and transmission of the relevant TOD information over the communication link. The TOD information continues to be transmitted until the TOD REQ is cancelled at the master station.

Such types of teleinformation as TC, TR and BTC are usually transmitted over the return communication channel, from MS to CS, and only in response to an appropriate request which specifies the type and volume of the information to be transmitted. Transmission continues as long as the current request remains in effect, and is discontinued as soon as that request is cancelled. From the CS RC SD, the incoming TI, TR or BTC information is routed to the control circuits of appropriate actuators, protection relay circuits and power system automatic devices and facilities sited in the controlled station area.

In some telecontrol systems, BTC information is transmitted spontaneously over the forward communication link. Such transmission commences with the arrival to the CS of a special BTC REQUEST pulse which discontinues the transmission of all other types of information in order that the communication channel could be used exclusively for the transmission of top-priority blocking telecommands. The need in CS-to-MS BTC transmissions may, for example, arise in a situation when the master station is equipped with, say, a central controller (such as that to control line frequency and restrict active power exchanges) governing a certain power object sited at the controlled station. If now the object circuitry or parameters change in such a way as to necessitate the blocking of the controller action, a BTC REQ signal will have to be generated and sent to the CS FC SD to discontinue transmission of all other types of teleinformation. Termination of the BTC transmission is usually realized by sending, over the return communication channel, a special signal cancelling the BTC REQ command.

The paths of the emergency BTC signals are not depicted in Fig. 5.4 because spontaneous BTC transmission is analogous of spontaneous TI transmission, the only difference being that the TI information is transmitted along with other messages (bringing about only a slowing down of the updating cycle), whereas the BTC information is transmitted on the exclusive-use basis, when the transmission of all other types of information is terminated.

Normal operation of multichannel PCM telecontrol systems requires that its transmit and receive subsets are properly synchronized. The sync reference is normally provided by the transmit subset clock pulses. The transmitter and receiver are locked into synchronism either by having the former generate special-purpose sync pulses (or sync pulse trains), or else by comparing the phase of the transmitter pulses with that of the receiver clock generator during transmission of information (this latter technique is known as inertia-type synchronization).

Multichannel PCM telecontrol systems can function in a simplex, duplex, or half-duplex modes. In the *simplex mode*, information is transmitted in one direction only (from the transmit to receive subset). The *duplex mode* implies simultaneous transmission of information in both directions. Finally, the arrangement whereby information is first transmitted over the forward path and then over the return path is referred to as *half-duplex*. The simplex mode is applicable to cyclic TM and TI transmissions only. Spontaneous TI transmissions can be organized in the half-duplex mode. Transmission of the TOD, TC, TR and BTC information is possible both in the duplex and half-duplex modes.

The requisite fidelity, accuracy, speed and reliability levels of the TM information transmission are contingent with a number of factors, the basic of which are the nature and waveform of each of the telemetered measurands and their role in the overall control process.

Application of PCM systems for cyclic transmission of telemetering information necessitates time and amplitude quantization of the signals involved. Quantization inevitably gives rise to the so-called digitization error, which can be defined as the sum of the amplitude quantization (static) and time quantization (dynamic) errors. As applied to the most frequently used step-wise interpolation technique and asynchronuous automatic access to the reproduced information during its input to the computer memory, the total root-mean-square error averaged over the maximum range of the telemetered measurand variations is given by

$$\bar{\delta}^2_{*\Sigma} = \frac{1}{12\mu^2} + 2\frac{D_x}{\Delta_x^2}\left[1 - \frac{1}{T_0}\int_{t_{tr}}^{t_{tr}+T_0} K_0(\tau)\,d\tau\right] \qquad (5.1)$$

where μ is the number of quantization levels of the A/D converter used; D_x is the dispersion of the measurand; Δ_x is the measuring scale, determined by the maximum possible range of the telemetered measurand; T_0 is the teleinformation updating (refreshment) time; t_{tr} is the transmission (transfer) time of a single TM message; $K_0(\tau)$ is the normalized autocorrelation function of the telemetered measurand.

For each PCM telecontrol system, the root-mean-square amplitude quantization error is constant, and conditioned only by the code word size used to transmit a single TM message. Therefore with $\overline{\delta}_{*\Sigma}$ given, the expedient information updating time of a particular telecontrol system will be determined by the dynamic component of the total digitization error which, as Eq. (5.1) clearly indicates, is determined by statistical characteristics of the telemetered measurands.

Multichannel PCM telecontrol systems can operate with any private (non-switched) communication channels. Used most extensively with such systems are non-switched channels organized by sub-multiplexing a standard VB channel with the help of appropriate sub-multiplexing equipment (SME).

In compliance with the CCITT recommendations, the majority of modern modulators and demodulators (modems) designed for transmission of discrete information, as well as the SME of standard telephone-grade communication channels are realized on the basis of unified structural and logical principles, with the predominant use of FM signals (see Section 5.5).

Transmission speeds. The practical range of transmission speeds is conditioned by the requisite information updating time and the information handling capacity of the telecontrol system components. The CCITT recommends that the following approximate relationship exists between the information transmission speed ν (bits per second) and the necessary frequency spectrum Δf (Hz)

$$\nu = (0.4\text{-}0.75)\,\Delta f \tag{5.2}$$

If all the measurands are transmitted with an equal updating time, then the requisite TM transmission speed over a given communication channel will be expressed as

$$\nu = \gamma\,(n+d)\,r_0 T_{0\min}^{-1} \tag{5.3}$$

where γ is the redundancy coefficient determined by the number of special auxiliary words (messages) needed to delimit individual cycles and synchronize the transmit and receive subsets; n is the number of information digits of the word used to transmit a single TM measurand; d is the number of auxiliary (error protection or check) word digits; r_0 is the number of measurands telemetered by a given telecontrol system; $T_{0\min}$ is the minimum updating time for all the measurands in question (the parameters for which the requisite updating time exceeds $T_{0\min}$ will be transmitted with a certain amount of redundancy).

Eqs. (5.2) and (5.3) help obtain a simplified formula by which to assess the information handling capacity of a PCM communication channel:

$$\Delta f_c = \gamma\,(n+d)\,r_0/[(0.4\text{-}0.75)\,T_{0\,\min}] \tag{5.4}$$

The specific cofactors of this product are conditioned by the telecontrol equipment chosen to best meet the requirements of a given automated dispatch control system.

In contradistinction to the cyclic mode, the spontaneous transmission mode implies that each next sample of the measurand value be transmitted only when the following inequality is true

$$|x(t) - x(t_i)| \geqslant |\delta_q|_{\max}$$

where $x(t)$ is the measurand current value; $x(t_i)$ is the measurand value transmitted last; $|\delta_q|_{\max}$ is the absolute value of the maximum admissible amplitude quantizing error.

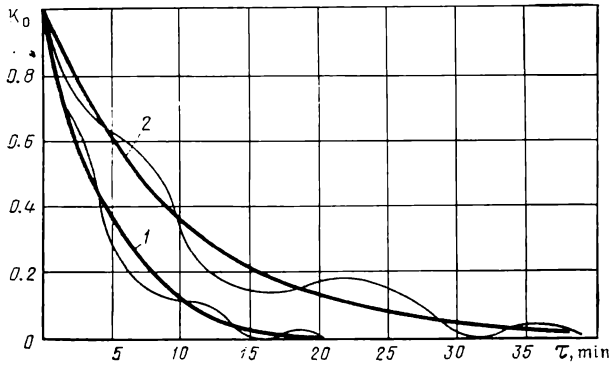


Fig. 5.5

The maximum dynamic error will then be given by

$$|\delta_{d.i}|_{\max} \leqslant 2|\delta_q|_{\max}$$

However, practical realization of a spontaneous TM transmission is far from easy, because it requires the use of transmit and receive subsets of a highly developed logical structure (on a par to the central processing unit of a digital computer). It therefore appears more practical to transmit the TM information at a variable sampling period, so that the updating cycle of each of the measurands would be determined by its most stable statistical characteristics. Statistical analysis of the charts representing variations of the active powers of power stations, voltage levels and power exchanges over intersystem nets has indicated that they can be treated as essentially random processes for which the steady-state condition can only be expressed through an autocorrelation function. The normalized autocorrelation functions for these processes are sufficiently accurately approximated by exponential functions of the form

$$K_0(\tau) = e^{-\tau/T}$$

where T is the time constant.

The chart of Fig. 5.5 depicts the normalized autocorrelation functions (thin lines) and relevant approximating functions (solid lines) of: *1*—power exchanges over intersystem nets and active power of power stations partaking in with the exponent time constant being $T = 300$ seconds; *2*—voltage at the net nodes and power of the stations not partaking in LFC-AGC, with $T = 600$ seconds.

With $z \ll 1$, a correlation function of the form e^z can be expressed by the first two terms of its expansion into a series, such that

$$e^z = 1 + \frac{z^2}{1!} + \frac{z^2}{2!} + \dots ,$$

Then, Eq. (5-1) can be re-written as

$$\bar{\delta}^2_{*\Sigma} = \frac{1}{12\mu^2} + \frac{D_x}{\Delta_x^2} \cdot \frac{T_0 + 2t_{tr}}{T}$$

wherefrom

$$T_0 + 2t_{tr} = \frac{\Delta_x^2 T}{D_x} \left(\bar{\delta}^2_{*\Sigma} - \frac{1}{12\mu^2} \right) \tag{5.5}$$

Most of the modern PCM telecontrol systems have their A/D converters designed for $\mu \approx 200$ (with μ being the number of quantization levels). If the total root-mean-square error is equal to $\delta_{*\Sigma} = 0.01$, application of Eq. (5.5) to the results of the statistical analysis of the condition parameters yields the following figures (see Table 5.1).

Table 5.1

Parameters	Statistical indices		T_0+2t_{tr}, s
	$\Delta_x / \sqrt{D_x}$, rel. units	T, s	
Exchanges of power over intersystem nets	10	300	2.9
Active power of stations partaking in LFC-AGC	11	300	3.5
Active power of stations not partaking in LFC-AGC	13	600	9.9
Voltage at monitored nodes	19	600	21.2

To ensure transmission of information with variable updating cycles, use can be made in multichannel PCM telecontrol system of multiple-commutator schemes, shown in a simplified form in Fig. 5.6. Here, the main commutator (I) is supplemented with two additional commutators (II and III) referred to as *sub-commutators*. The main commutator polls the measurands requiring the shortest

updating time ($T_{0\min}$), and "accesses" the two sub-commutators. Sub-commutator II is "accessed" every time the main commutator is in position *1*. Since sub-commutator II is designed for a cyclic polling of four measurands, $T_{0II} = 4T_{0\min}$. Sub-commutator III is "accessed" every time the main commutator is in position *3*, and the updating time of each of that sub-commutator eight measurands equals $T_{0III} = 8T_{0\min}$.

If we denote the commutator capacity as S_0, then the transfer (transmission) time of one measurand over the communication channel will be expressed as

$$t_{tr} = T_{0\,\min}/(\gamma S_0) \qquad (5.6)$$

while the requisite TM transmission speed will be given by

$$\nu = \gamma (n + d) S_0 T_{0\min}^{-1}$$

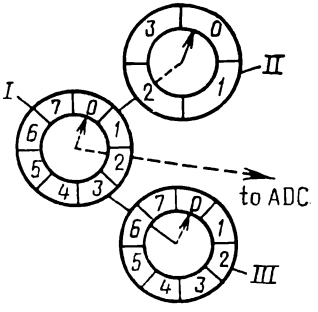


Fig. 5.6

In order that the telemetered measurands could be transmitted at the requisite updating cycle, the capacity of each sub-commutator must meet the condition

$$S_i = T_{0i}/T_{0\min} \qquad (5.7)$$

where T_{0i} is the pre-assigned updating cycle for the i-th group of measurands.

Denoting

$$\alpha_i = (T_{0i} + 2t_{tr})/(T_{0\min} + 2t_{tr})$$

and considering Eqs. (5.6) and (5.7), we can write that

$$\alpha_i = (\gamma S_0 S_i + 2)/(\gamma S_0 + 2)$$

whence

$$S_i = \alpha_i + 2(\alpha_i - 1)/(\gamma S_0) \qquad (5.8)$$

In practice, S_i is rounded off to the nearest smaller integer.

Most of the existing mutlichannel PCM telecontrol systems are capable of handling 10, 20 or 30 measurands, the average redundancy coefficient being $\gamma = 1.2$. Under such conditions, the requisite sub-commutator capacity can be found from Eq. (5.8) using the α_i values deduced from Table 5.1. Some examples of the resultant capacity figures are listed in Table 5.2. Analysis of these figures indicates that to be able to effect variable-updating transmission of its measurands, a telecontrol system should have available two sub-commutators in addition to the main commutator used to poll exchanges of power over power lines and active powers of the stations integrated

under an LFC-AGC* system. The measurands polled by the main commutator at an updating cycle of $T_{0\min}$ will then total

$$r_0 = S_0 - 2$$

The first sub-commutator must have a capacity of $S_1 = 3$, and poll the active power values of stations not encompassed by the LFC-AGC system. The capacity of the second subcommutator turns out to be dependent on that of the main commutator. Thus, with $S_0 = 10$ the capacity of the second sub-commutator will be $S_2 = 8$. With a larger-capacity main commutator, $S_2 = 7$.

It should be noted that with the type of modulation presently discussed, there exists a direct relationship between the transmission speed and the spectrum of frequencies required to effect the transmission. From this point of view, information transmission at variable updating cycles ensures a better utilization of available communication channels, because it permits more measurands to be transmitted within one and the same frequency spectrum.

Table 5.2

S_0	S_i		
	α_i=1.2	α_i=3.4	α_i=7.3
10	1.23	3.8	8.35
20	1.22	3.6	7.83
30	1.21	3.5	7.65

The total number of measurands that can be transmitted over a single communication channel in the variable-updating cycle mode constitutes $S_0 - 2 + S_1 + S_2$, while the number of measurands of equal updating cycles transmittable over the same channel is merely S_0. It follows then that the utilization factor (β) of a given communication channel can be expressed as the ratio

$$\beta = (S_0 - 2 + S_1 + S_2)/S_0 \qquad (5.9)$$

TM transmissions at variable updating cycles effectively mean fewer messages transmitted per unit of time and, eventually, a lighter load for the computer accepting and processing the transmitted teleinformation. With a total of $S_0 - 2 + S_1 + S_2$ parameters of variable updating cycles transmitted over a communication channel, the estimated rate of arrival of the incoming messages to the computer would equal

$$C_1 = \gamma S_0 / T_{0\min}$$

* LFC-AGC = Load Frequency and Automatic Generation Control.

On the other hand, transmission of the same number of measurands of one and the same updating cycle $T_{0\min}$ yields an arrival rate given by

$$C_2 = \gamma (S_0 - 2 + S_1 + S_2)/T_{0\min}$$

The conclusion to be drawn from the above is that the computer load (defined as the TM information accepted for processing) is reciprocal to the quantity expressed by Eq. (5.9).

With the TM information transmitted at variable updating cycles defined by Eq. (5.5), a range of values of each measurand can be obtained at the receiving end. Step-wise interpolation of these values is capable of yielding a truthful (in terms of root-mean-square errors) approximation to the original functions. Such an approach to representing the actual processes and phenomena characterizing the status and functioning of the power system(s) makes feasible an automated (man-aided) solution of a number of supervisory, managerial, prognostication and optimization problems.

Teleinformation in LFC-AGC systems. The facilities of automatic telecontrol systems are intended for transmission of appropriate measurands from the controlled stations (such as power stations and sub-stations) to the master station, and transmission of corresponding telecommands back to the controlled stations. The transmission of the TM and TC information must ensure the requisite quality of the control process. The admissible delay between an event at the input and a corresponding response action is determined by the time constant of the control loop, the updating cycle and transfer time of the TM and TC information, and the allowable deviations of the controlled measurands from their pre-assigned ratings.

Roughly, the relationship between the control loop time constant and the input signal frequency can be expressed as $f_{\max} \approx 1/T_l$, where $f_{\max}$ is the maximum frequency of the input signal; T_l is the time constant of the control loop.

Compared with the frequency, intersystem power exchanges are characterized by higher speeds and likely deviation ranges. Thus, the shortest period of the power exchange deviations liable to upset normal functioning of several parallel power systems (and therefore to be controlled by the LFC-AGC system) constitutes some 6 seconds.

Restriction of the active power exchanges requires that the control function in the LFC-AGC system be of the following form:

$$F = \frac{1}{T_{int}} \int_0^t (P(t) - P_0)\, dt$$

where T_{int} is the constant of integration in the LFC-AGC system; $P(t)$ is the current value of the power exchange; P_0 is the pre-assigned value of the power exchange.

In the case of a discrete transmission of the TM information with an updating cycle of T_0, the control function will be given by

$$F = \frac{1}{T_{int}} \sum_{i=1}^{i=\frac{t}{T_0}} (P_i - P_0)\, T_0$$

where P_i is the value of the power exchange transmitted by the telecontrol system in the i-th sample.

In the above mode of transmission, each single value of P_i will be measured with a total error maximum of

$$\delta_{\Sigma max} = \delta_{q.max} + \delta_{d.i.max} = \left(\frac{1}{2\mu} + 2\pi f_{max} T_0\right) P_{max}$$

where $\delta_{q.max}$ is the maximum amplitude quantizing error of the telemetered measurand; $\delta_{d.i.max}$ is the maximum error of step-wise interpolation (dynamic error); P_{max} is the maximum admissible active power exchange value.

If the TM and TC information is transmitted at equal updating cycles and a disturbance of some sort forces the power exchange to deviate from its rated value at instant t_0, the control function will have an error whose maximum value over a period of $t = t_0 + T_{int}$ will be given by

$$\delta_{F\,max} \approx \frac{1}{T_{int}} \sum_{i=\frac{t_0}{T_0}}^{i=\frac{t_0+T_{int}}{T_0}} \left(\delta_{q.max} T_0 + \frac{1}{2}\delta_{d.i.max} T_0\right)$$

$$= P_{max}\left(\frac{1}{2\mu} + \pi f_{max} T_0\right)$$

The rated value of power exchange, P_0, is chosen to be below the maximum value postulated by the stability criterion by $B = (0.2\text{-}0.3)\, P_{max}$.

In the LFC-AGC system, teleinformation must be transmitted at updating cycles ensuring an efficient correction of all power exchange deviations from the rated value liable to upset stability of the parallel power systems. For this reason, the most expedient teleinformation updating cycle is the one with which the condition

$$P_{max}\left(\frac{1}{2\mu} + 2\pi f_{max} T_0\right) < B$$

could be met.

Thus, with $B = 0.2 P_{max}$, $f_{max} = \frac{1}{6}$ Hz and $\mu = 200$, the most expedient information updating cycle would be $T_0 < 0.38$ second.

LEC-AGC systems pose stringent requirements on the reliability and accuracy of teleinformation transmission. To meet these requirements, the information essential to the functioning of the LFC-AGC systems is normally transmitted by dedicated telecontrol equipment over specially allocated double-redundancy communication links.

5.3. Information Accuracy

The accuracy of information reception is one of the most important characteristics of any communication system. If no safeguards are provided to protect the transmitted information from distortion, its accuracy at the receiving end would be determined first and foremost by the characteristics of the communication link used. Thus, the average error rate in conventional telephone-grade channels constitutes some 10^{-2} to 10^{-4}, or one error in 100 to 10 000 transmitted messages. Therefore all modern information and data transmission systems (and multichannel PCM telecontrol systems are no exception) employ special error prevention and protection techniques allowing significant improvements to be made in the accuracy of information transmission over noisy communication channels.

The principal error protection technique is coding of the transmitted information. The characteristic feature of many a telecontrol system is that each of the transmitted messages is protected through coding on a strictly individual basis. The concept of such a coding consists in supplementing the message to be transmitted with a certain redundant information that would eventually provide the error detection or even error correction capability. The codes used for the purpose have been named *error-detecting* and *error-correcting codes*, respectively. One of the simplest coding techniques ensuring an error detection capability is the parity check coding widely employed in digital computers. The parity check coding is realized by adding to the source information an extra bit (or a group of such bits) whose state depends on whether the number of units in the code of a given message is odd or even. If that number is even, the parity check bit assumes the state of a 0. Otherwise, it will be set to a 1. An oddness check coding is also possible, with the check bit assuming the opposite states.

In multichannel PCM telecontrol systems, use is widely made of Hamming codes, so named after their author, the American scientist R. W. Hamming. The use of Hamming codes permits correction of all single errors (a capability known as single-error correction, or SEC) as well as detection of even-number errors, including double errors (this latter capability is known as double-error detection, or DED).

R. W. Hamming was first to give a formal definition to the notion of code distance (which is why it is sometimes called the Hamming

distance). Now, a *code distance* is the number of digits in which code words differ. The minimum code distance is then the number of places in which digits differ between code words. In other words, the minimum code distance is the minimum number of binary digits that must be altered to have a given code word changed into another one.

A code of minimum distance d can help detect no less than $(d-1)$ errors. With information transmitted as code words of n binary digits of which m are information-carrying and $k = n - m$ are check digits, the number of SEC digits must meet the condition

$$2^k \geqslant m + k + 1. \tag{5.10}$$

For instance, if each of the transmitted code words contains between 5 and 11 information-carrying digits, the minimum number of check digits is $k = 4$, which means that a total of four binary check digits is necessary and sufficient to correct a single error in code words represented in a 5- to 11-digit format.

The code distance between two code words is characterized by the number of places in which these two words differ. In stricter terms, the code distance between word $A = (a_1, a_2, a_3, \ldots, a_n)$ and word $B = (b_1, b_2, b_3, \ldots, b_n)$ is given by

$$D(A, B) = \sum_{i=1}^{n} (a_i \oplus b_i)$$

where the sign $\oplus$ denotes a modulo-2 addition equivalent to the usual digit-by-digit addition without carry, or the logical "exclusive or" (XOR) operation. For example, the code distance between words 001011 and 101001 is equal to two.

Single-error detection involves application of the technique also devised by R. W. Hamming. This technique consists in the following:

(a) the messages to be transmitted are numbered $0, 1, 2, \ldots, N$;

(b) the messages (words) are written in the binary notation using an equal number of binary digits (say, m) per each word;

(c) the minimum code distance is determined on the basis of Eq. (5.10);

(d) the words are arranged so that their information-carrying digits are preceded by the k check digits;

(e) the state of each of the k check digits is assumed to be conditioned by the state of the information-carrying digits in compliance with the following identities

$$\left.\begin{aligned} &X_1 + X_3 + X_5 + X_7 + X_9 + X_{11} + \ldots = 0; \quad (S_1) \\ &X_2 + X_3 + X_6 + X_7 + X_{10} + X_{11} + \ldots = 0; \quad (S_2) \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ &X_4 + X_5 + X_6 + X_{12} + X_{13} + X_{14} + \ldots = 0. \quad (S_8) \end{aligned}\right\} \tag{5.11}$$

Under such conditions, the values of the information-carrying digits non-ambiguously determine the values of the respective check digits.

As can be readily seen, each word at the receiver must meet the identities of (5.11) as long as the information is being transmitted correctly. If the identity S_1 is met, then it is assumed that $S_1 = 0$. Otherwise, $S_1 = 1$. According to the work of Hamming, the position of an incorrectly received information-carrying digit is conditioned by a binary number formed of states S_i of Eq. (5.11) written as $l = S_\theta, \ldots, S_2, S_1$.

The method of error protection outlined above is employed in Soviet-made telecontrol systems of the MKT type.

Apart from the Hamming codes and combinational codes in which the number of 1's and 0's is constant (for instance, the code C means that there will always be two 1's in each 5-element code combination), use is also made in practical systems of the so-called correlation codes. One example is the Soviet-made STIMUL system for multichannel PCM telecontrol, in which two elementary signals (a pulse-plus-pause for a 1 and a pause-plus-pulse for a 0) are used to convey each code digit, so that an equal number of pulses and pauses is required to transmit any one code word.

5.4. Data Transmission Systems

The extensive prolifiration of computers into the world of production management and control has urgently necessitated the need for a means of some sort that would allow the computers at various levels of control hierarchy to directly interchange large volumes of data in a fast, reliable and accurate manner, either completely automatically (under control of computer software) or following the instructions of a human operator as to the direction, speed, type and volume of the information (data) exchange. Most suitable for use as such a means turned out to be the existing VB channels equipped with special terminal facilities incorporating sub-multiplexing equipment and data transmission systems proper.

The purpose of data transmission systems (DTSs) is to ensure transmission of alphanumeric data and special auxiliary characters in the form of binary-signal codes suitable for input into computers, as well as to provide the user with the necessary computation results in a man-readable format. The data intended for transmission can be input to the DTS either from special data-carrying media (such as punched or magnetic tapes), or directly from the computer memory or storage. At the point of destination, the data can likewise be carried onto a storage medium of some sort or input directly into computer memory for further processing or storage. Accordingly, several basic data transmission schemes can be identified: "tape-to-

tape", "tape-to-memory", "memory-to-tape", and "memory-to-memory".

In the tape-to-tape scheme, each character of the data to be transmitted is punched on a tape as a combination of holes corresponding to a 5- to 8-digit code. The thus prepared tape is then fed into a tape reader which, as its name implies, reads out the encoded data and converts it into pulses of a telegraph-type code. The pulses are accepted by the DTS send station which transmits them over the communication channel. At the receiving end, the DTS receive station converts the telegraph-code pulses into signals driving a tape punch unit that puts out a punched tape that is an exact replica of the source tape.

As often as not, the user DTS station (set) is required to incorporate not only data-reading equipment, but also printing facilities to allow the user to get a printed (or "hard" as it is sometimes called) copy of the transmitted information. Clearly, under such conditions an efficient utilization of the communication channel and the data transmission system as a whole can hardly be ensured unless the rate of data input at the send end is commensurable with the data transmission speed over the communication channel and the rate of its output at the receive end. In other words, the input, transmission, reception and output of information and data must be synchronized.

A distinctive feature that sets the DTS apart from other systems capable of handling and transmitting large volumes of alphanumerical information is its high accuracy. This is attained through the application of the so-called "automatic request for repetition" (ARQ) concept, which provides for a special auxiliary return communication channel to carry to the originator the requests for a repeated transmission of the information found to be incorrect. The prerequisite for a successful application of this transmission technique is segregation of all the information (data) being transmitted into individual information blocks (IB). This is accomplished with the aid of special-purpose storage units (see Fig. 5.7) of the TDS send and receive stations.

The useful information (UI) to be transmitted is entered into the send station storage unit (SU) which supplements it with special check digits (CD). Unlike PCM telecontrol systems, data transmission systems rely mostly on the so-called cyclic codes to provide the error-control capability for the information blocks. Without going into undue details, cyclic coding can be said to consist in XORing the useful information with a certain constant obtained by means of a special polynomial, and adding the remainder to the useful information. At the receiver, the operation is repeated, and disagreement between the two remainders points to an information error (if any).

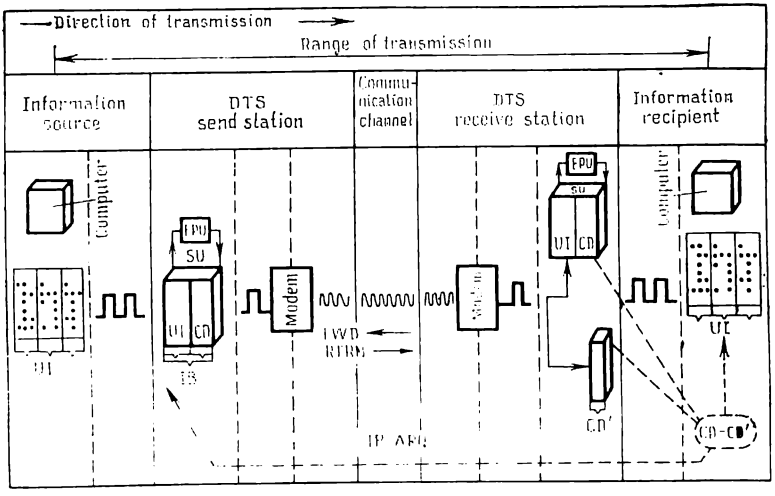


Fig. 5.7

The check digits are generated at the send and receive stations by special error protection units (EPU). The send station EPU generates the check digits and adds them to the UI to form an IB for transmission over the communication channel. Transmission is organized in such a way that information digits are sent first, with the check digits following. At the receiver, the binary signals of the useful information are entered into the SU and at the same time are routed through the EPU. By the time the useful information has been transmitted, the receive station EPU will have generated the appropriate check digits. Now, if the information is transmitted correctly (without errors), the check digits (CD) produced by the receive EPU will be in full agreement with the check digits (CD') generated at the send end and transmitted over the communication channel along with the useful information.

Most of the DTS units are usually two-way devices, capable of functioning both in the transmit and receive modes.

DTS block diagram. The block diagram of Fig. 5.8 shows a data transmission system as consisting of the following basic parts:

—an information input device ($D_{info\ in}$), usually taking the form of a telegraph transmitter, a tape reader, etc.

—an information output device ($D_{info\ out}$), such as a tape punch, printer, etc.;

—an input/output interface (IOI);

—an input/output control unit (IOCU);

—a storage unit (SU);

—an error protection unit (EPU);

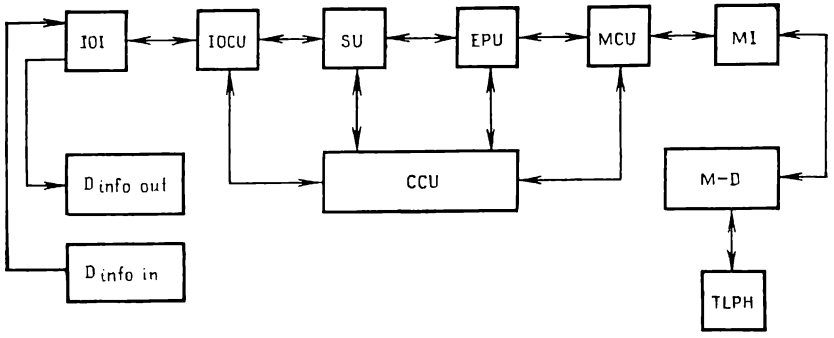


Fig. 5.8

—a modulator/demodulator (modem) control unit (MCU);
—a modem interface (MI);
—a central control unit (CCU);
—a modem (M-D);
—a telephone set (TLPH).

Described below is the purpose and operation of each of these parts.

Input/output interface provides a logical and functional compatibility between the DTS and the information input/output devices it works with.

Input/output control unit switches the input/output devices on and off and, more importantly, brings into agreement the rates at which the information is being input and output, in order that the available communication channel would be utilized with a maximum efficiency possible. Besides, it allows the information to be put in and brought out in various code formats containing from five to eight binary digits per one information character transmitted.

In a number of applications, each input information character needs to be checked for parity. The input/output control unit can be used to select the desired check mode, or let the information through unchecked. In the check mode, an error in the transmitted information makes the control unit stop the associated input device (thus terminating further transmission) and generate an "abnormal end" (ABEND) signal.

Storage unit performs the functions of an intermediate storage for the incoming and outgoing information. In modern data transmission systems, use is most widely made of storage units built around MOS (metal-oxide-semiconductor) integrated memories that are fast, compact, reliable and not power-thirsty. The requisite capacity of the storage units is consistent with the length and structure of the information blocks transmitted. Although these vary from one sys-

tem to the next, the majority of DTS operating at transmission rates of between 200 and 1 200 bauds (bits per second) have their information blocks made up of three parts: a prefix, an information part (message) and check digits.

The purpose of the prefix is to delimit and identify the sequentially transmitted information blocks, as well as to synchronize the operation of the send and receive stations. The prefix and check parts of one information block normally contain between 4 and 16 digits, respectively, while the information part usually includes 120 or 240 binary digits. Thus, the overall length of a typical information block constitutes 140 or 260 binary digits.

With the view of achieving a higher information transmission rate, the storage unit capacity is standardly chosen to be sufficient to accommodate a tleast two (often more) information blocks. For example, the storage units of the Soviet-made ACCORD-1 200 system have a capacity of 260 and 132 binary digits, respectively. Structurally, each information block of this system consists of 4 auxiliary (prefix), 240 or 112 information, and 16 check binary digits. The data intended for transmission arrive to the transmitter in a parallel or serial code format. The transmitter converts the data into information blocks each of which is error-protected against possible communication channel noise by being cyclically encoded as a generator polynomial of the form $F(X)=X^{16}+X^{12}+X^{5}+1$. The data are continuously fed into the forward channel modulator in a serial-code format and keyed at a speed of 600 or 1 200 bauds.

At the receive station, the forward channel demodulator converts the incoming signals into serial-code information blocks and routes them into the error protection unit (EPU) and storage unit (SU). The information blocks in which no errors have been detected are brought out of the DTS, while those with errors are erased from storage, and a request is sent to the originating station for their repeated transmission. With no errors detected, a "positive acknowledge" signal is relayed over the return channel (which means that the latter will be in a 0 state). Otherwise, the return channel will assume the state of a 1, thus signalling that an "automatic request for repetition" (ARQ) is pending.

In order to intensify the rate of data exchange and utilize the communication channel more efficiently, the transmitter never stands idle for an acknowledge (ACK) signal to arrive, but rather resumes transmission of the upcoming information block while storing the previously transmitted one in its storage unit. It is only during transmission of the next-in-line information block that the transmitter receives an ACK or ARQ signal from the receive station. If the signal signifies ARQ, the transmitter re-transmits the data of the block stored in the storage unit. The capacity of the storage unit must be sufficient to hold two information blocks.

The prefix part of an information block provides for cyclic numbering of the transmitted information blocks, and serves to generate the synchronization, pause and end-of-message identifiers. The first information block transmitted after the initial phasing is assigned the block identifier A, with subsequent blocks assigned the identifiers B, C, A, B, C, A, and so on, respectively. This arrangement precludes a loss or double reception of information blocks by the receiver due to noise in the communication channel in all modes of operation.

With the information part of a block being 240 binary digits long, the introduction of 4 auxiliary (prefix) and 16 check digits means a redundancy of a mere 8%. Yet, this turns out to be sufficient to ensure a transmission accuracy of no more than one error in 10^6 transmitted characters, and an average error rate in the communication channel of $2 \cdot 10^{-4}$ per character maximum.

Error protection unit (*EPU*) is intended to improve the accuracy of the transmitted information by generating auxiliary check digits whose state is conditioned by the information block being transmitted.

The CCITT recommends that for the purposes of error control, data transmission systems employ cyclic codes with a generator polynomial of the form

$$F(X) = X^{16} + X^{12} + X^5 + 1 \qquad (5.12)$$

with which up to 16 check digits can be organized.

The cyclic (polynomial) encoding means that each message consisting of k binary digits is modulo-2 divided by the generator polynomial, with the remainder comprising $(n - k)$ binary digits providing the error-control capability.

The cyclic code is defined through the notion of the generator polynomial $F(X)$ of degree $n - k$. A polynomial whose degree is less than n is called the code polynomial, accepted for transmission when (and only when) it is even divisible by the generator polynomial $F(X)$. Note that a sum of two code polynomials is itself a code polynomial. If $\varphi_1(X)$ and $\varphi_2(X)$ are polynomials of a degree smaller than n, and are divisible by $F(X)$, then their sum $\varphi_1(X) + \varphi_2(X)$ will likewise be a polynomial of a degree smaller that n, also divisible by $F(X)$.

If X is a simple factor for $F(X)$, then it is also a simple factor for any other coder polynomial and, consequently, the X_0 coefficient will be zero in any code polynomial. Since such polynomials are clearly of no practical value, use is made of only those polynomials for which $F(X)$ is not divisible by X.

In the general case, a code polynomial can be obtained by simply multiplying any polynomial of a degree less than k by $F(X)$. For DTS applications, however, more practical turns out to be a some-

what different technique whereby the message information digits are expressed through the higher-degree X coefficients, while its check digits are represented by the lower-degree X coefficients.

For encoding the polynomial $M(X)$ corresponding to a certain message, one must find the remainder of $X^{n-k}M(X)$ divided by the generator polynomial $F(X)$, such that

$$X^{n-k}M(X) = F(X)\,Q(X) + R(X) \tag{5.13}$$

where $Q(X)$ is the quotient; $R(X)$ is the remainder of $X^{n-k}M(X)$ divided by $F(X)$.

Since the modulo-2 subtraction is equivalent to the modulo-2 addition,

$$V(X) = X^{n-k}M(X) + R(X) = Q(X)\,F(X)$$

which is multiple of $F(X)$. The conclusion is that $V(X)$ is a code polynomial. Importantly, the coefficients of the polynomial $V(X)$ are, at the X degrees higher than k, equal to the coefficients of $M(X)$ which are essentially the message information digits. The number $(n - k)$ of the lower-degree X coefficients of the polynomial $V(X)$ are equal to the $R(X)$ coefficients and are thus the check digits. Thus, in the initial phasing (synchronization) mode, the send station of the ACCORD-1 200 system transmits into the communication channel a special four-digit binary code 0101 known as the *sync block identifier*. This identifier is generated by the input/output control unit and reaches the forward channel modulator via the error protection unit which supplements it with the remainder of $X^{n-k}\,M(X) = X^{16}(X^2 + 1)$ divided by $F(X) = X^{16} + X^{12} + X^5 + 1$. This remainder takes on the form of $R(X) = X^{14} + X^{12} + X^7 + X^5 + X^2 + 1$ or, in the binary notation, 0101000010100101. The thus coded signal known as the *sync combination signal*, is sent to the forward channel modulator following the sync block identifier.

In the initial phasing mode, the error protection unit of the receive station operates as a 16-digit shift register to which the incoming data is successively fed from the forward channel demodulator. The register is provided with a special sync combination decoder that puts out a special signal transferring the receive station into the "receive" mode if the received information coincides with the above-mentioned binary expression.

Since in that mode the state of the check digits is conditioned by the state of the information digits, the check digits turn out to be generated twice, by the send and receive stations independently. The check digits received from the forward channel are compared against those obtained at the receiving end of the link. If both are in full agreement, the transmitted information is assumed to have been received correctly (without errors). A disagreement between

the two sets of check digits is indicative of an error, and thus necessitates a repeated transmission of the incorrectly received information block.

A coded message containing an error can be expressed as

$$H(X) = V(X) + E(X) \tag{5.14}$$

where $V(X)$ is the undistorted coded message; $E(X)$ is the polynomial with non-zero terms of each erroneous digit.

Considering the properties of modulo-2 addition, $H(X)$ can be viewed as the source polynomial with its erroneous digits altered. A failure of $H(X)$ to divide by $F(X)$ thus means that an error has occurred. If, however, $H(X)$ does divide by $F(X)$, the message will have to be assumed correct, even though there may be undetected errors. Indeed, since the criterion governing the choice of $V(X)$ has been its divisibility by $F(X)$, the polynomial $H(X)$ must divide by $F(X)$ if (and only if) $E(X)$ divides by $F(X)$ as well. Therefore the error combination $E(X)$ will be detected if (and only if) it fails to divide by $F(X)$. A conclusion follows then that for the error control to be effective, the source polynomial must be selected so that no conceivable error combination would divide by $F(X)$.

Modem control unit (MCU) helps organize transmission of discrete signals over communication channels at most expedient speeds and in a most convenient manner. In majority of modern data transmission systems, data is conveyed synchronously at speeds of 600 and 1 200 bauds.

The CCITT has ruled that certain standard information transmission speeds be used with existing communication channels. Thus, the recommended standard speed for telegraph channels is 50 bauds, although additional speeds of 100 and 200 bauds are also provided. With telephone channels, the standard speeds are 200, 600 and 1200 bauds, although still higher speeds of 1 800, 2 400, 3 000, 3 600, etc, bauds (i.e., those multiple of 600) are also under consideration. It has also been decided that FM would be treated as the basic modulation method in wire communications, because it yields an approximately the same error probability level as angle modulation, but is simpler to realize.

The modem control unit can help organize information exchange in the following modes:

—one-way transmission (reception) of information over two- or four-wire communication links (simplex mode);

—two-way alternating transmission/reception of information over two-wire communication links (half-duplex mode);

—two way simultaneous transmission/reception of information over four-wire communication channel (full duplex, or simply duplex, mode).

Apart from handling the information traffic over the forward channel, the MCU is used to organize a simultaneous return transmission of auxiliary signals at a maximum speed of 75 bauds.

To be able to effect through connections over switched communication channels, the modem control unit is equipped with a telephone set connected in a "director-secretary" scheme to simulate the main telephone set. The unit must connect calls and control them both in the automatic and operator switching modes. Four basic operating conditions are identified: TELEPHONE (establishing a link and effecting the initial phasing), TRANSMIT, RECEIVE, and CHECK.

In addition to these, a fifth operating condition known as STANDBY is sometimes provided to allow the information transmission (reception) to be temporarily discontinued (manually or automatically) without a loss of synchronism between the send and receive stations.

In the TELEPHONE mode, the communication channel is connected to the telephone set, and power is applied only to the standby device that accepts calls from the send station(s) and activates the DTS equipment. In the TRANSMIT and RECEIVE modes, the modem control unit couples the communication channel to the forward and return modems and applies power to all the DTS parts needed to transmit (receive) the necessary information.

In the CHECK mode, the communication channel is connected to the telephone set, power is applied to all the units and devices of the DTS, and the output of its transmit section is coupled to the input of the receive section. In this mode, the clock pulse generator operates as a "dot generator" to feed the modulator with a string of pulses simulating the forward communication channel in operation. Besides, the clock pulse generator supplies all the DTS units and devices with signals of appropriate frequencies governing the operational speed of the send and receive sections and the phase equalization and error protection units.

Modem interface (MI) serves to provide a logical and functional interface between the modem and its control unit. The basic functions of the send station modem are to modulate the forward channel with the information source signals and to demodulate the FM signals accepted from the return channel (ACK or ARQ).

The CCITT recommends that 600-baud forward channels employ a 1 500-Hz carrier with a frequency deviation of ± 200 Hz, while 1 200-baud channels utilize a 1 700-Hz carrier with a frequency deviation of ± 400 Hz. The recommended transmission speed over the auxiliary return channel is 75 bauds, the corresponding operating frequencies being 390 and 450 Hz (at a 420-Hz carrier).

Since telephone-grade links standardly have their lower cutoff frequencies at 300 Hz and the DTS information signals entering the

forward channel modulator have a broader frequency spectrum (ranging from DC to 600 Hz), a need clearly arises to so convert the spectrum of the source signal that it would fall within the link passband. In data transmission systems, this is achieved by having the information signal modulate (in frequency or phase) a higher-frequency carrier chosen to be consistent with the requisite transmission speed (the higher the speed, the higher the carrier).

It should be noted that at high speeds straightforward modem structures can barely fulfill their functions successfully. Indeed, at 1 200 bauds the width of the signal pulse is only 0.83 ms, which constitutes a mere 1.08 of the lowest operating frequency period. For this reason, use is usually made of stepped-up carriers and appropriate auxiliary devices to down-convert the useful signal to within the voice-frequency band. This conversion can be accomplished either by conventional heterodining or through application of purely binary techniques (such as dividing a frequency with the help of a string of binary counters).

While yielding somewhat better results in terms of quality, the latter technique requires the use of a greater number of logical elements and thus complicates the equipment. One example is provided by the Soviet-made ACCORD-1200 data transmission system, in which a 153.6-kHz output of a master clock generator is down-converted by conventional flip-flop dividers into a number of frequencies: 38.4, 19.2, 9.6, 4.8, 1.2, 0.6, 0.3, 0.075, and 0.0375 kHz.

At a speed of 1 200 bauds, the 2.1-kHz signal needed to transmit a positive pulse of the source information is obtained by summing the 153.6-, 38.4- and 9.6-kHz signals and dividing the result by means of a discrete divider with a division ratio of $k = 96$. The lower operating frequency signal of 1.3 kHz is obtained with the help of the same divider to which a signal of $153.6 + 9.6 - 38.4 = 124.8$ kHz is applied.

If the information is to be transmitted at a speed of 600 bauds, the upper and lower operating frequencies are obtained as a result of $(153.6\text{-}9.6 \pm 19.2):96$. This means that with the 19.2-kHz component added, the signal will enter the divider at 163.2 kHz and emerge out of it at 1.7 kHz. If, conversely, the 19.2-kHz component is subtracted, the divider input will be a 124.8-kHz signal, which corresponds to the lower operating frequency of 1.3 kHz at the divider output.

Since the frequency add and subtract operations are essentially discrete, the divider output frequencies tend to vary somewhat. In fact, they are coincident with the rated upper and lower operating values only during the time intervals equal to or multiple of the repetition period of the 9.6-kHz pulses that eventually condition the division cycle. In synchronous work when speeds are 1 200 and 600 bauds, an integer number (8 and 16, respectively) of division

cycles falls within one transmission cycle. As a result, the operating frequencies during one transmission cycle are, on the average, equal to their respective ratings, and no phase incursions are experienced at the transmission cycle boundaries.

In asynchronous work, an arbitrary (including a non-integer) number of division cycles may fall within one transmission cycle. Since the extra pulses are distributed unevenly within individual division cycles, the average per-transmission-cycle operating frequency turns out to be dependent on what segment of one division cycle has been added to the integer number of these cycles. As is readily apparent, maximum deviations of the operating frequencies from their rated values will take place during maximum phase incursions at the cycle boundaries. Special investigations have proved though that even the worst-case phase incursions produce the arrival curve distortions of a mere 3%.

The FM signal needed for 75-baud transmissions over the return channel is obtained with the help of a constant-ratio ($k = 48$) frequency divider. The basis of the divider input is provided by a 20.16-kHz signal resulting from summing trains of pulses at 19.2 kHz and 0.96 kHz (the latter is obtained by dividing 4.8-kHz pulses by a factor of 5). The upper and lower operating frequencies are derived by adding to and subtracting from this basic 20.16-kHz signal a train of pulses at 1.5 kHz, which in its turn is obtained by mixing 1.2-kHz and 0.3-kHz pulses. With the 1.5-kHz pulses added, the divider output corresponds to the upper operating frequency of 450 Hz. With these pulses subtracted, the divider puts out a signal corresponding to the lower operating frequency of 390 Hz.

To extract information from the incoming FM signal, the forward channel demodulator employs frequency discriminators made up of pairs of oscillatory circuits stagger-tuned with respect to the center frequency. However, the typically small difference between the carrier and the modulating frequency necessitates the use of a sharp-cutoff low-pass filter to separate the two, and this cannot but impair the filter frequency characteristic within its transmission band. This limitation is usually overcome by converting the FM signal spectrum towards higher frequencies (7 100 through 8 700 Hz).

Since various factors may bring about variations of the incoming signal level, a limiting amplifier is standardly interposed in front of the modulator. The aim is to make the modulator operation essentially independent of the input signal level and to eliminate the unwanted amplitude modulation of the FM signal that might otherwise distort the signal duration.

The discriminator oscillatory circuits convert the FM signal into an amplitude-modulated signal which is then envelope-detected and smoothed by means of a detector and a filter. Finally, the demodulator output device converts the resulting signal into square pulses of

requisite amplitude, thus, reconstructing the original modulating signal.

The return channel demodulator has no frequency converter because the carrier and the modulating frequency are spaced far enough from each other to make practical realization of the post-detector filter quite feasible. Otherwise, reconstruction of the original signal from the FM carrier is not different from the forward channel.

The block diagram of Fig. 5.9 shows a sub-multiplexing system utilizing a frequency-division multiplex principle to effect simplex transmissions of data over a VB channel at speeds of 600 and 1 200 bauds. The information block (IB) is applied to the system from the error-protection unit (EPU) of the send station. The forward channel modulator (FCM) translates the IB into a FM signal which, via a gain control circuit (GCC), a directional filter (DF), a differential system (DS) and the TLPH-DTS switch (S), enters the VB channel. The receive station of the data transmission sub-multiplexing equipment accepts the FM signal from the channel and routes it through its S, DS and DF to a limiting amplifier (LAMP). The purpose of this amplifier is to boost the incoming signal and produce an output that would remain essentially constant under variations of the input level of between —0.5 and —4.5 nepers. The thus amplified and amplitude-limited signal then goes to the forward channel demodulator (FCD) that uses it to put out negative-going pulses (1's) when the signal frequency is 1 300 Hz, and positive-going pulses (0's) when it is 1 700 (2 100) Hz. The demodulator pulses are checked in the EPU and are sent to appropriate output devices or into the computer memory. If the information is found to contain an error, the EPU will generate an automatic-request-for-repetition (ARQ) signal which, at a signalling speed of 75 bauds, is applied to the return channel modulator (RCM) operating at the center frequency $f_c = 420$ Hz with a ± 30-Hz frequency deviation.

The frequency-modulated ARQ signal is passed via the GCC, DF and DS into the VB link which carries it back to the send station. There, the signal passes through the DS, DF and GCC into the return channel demodulator (RCD). In response to the ARQ signal, the RCD signals the EPU that the erroneously received information block is to be re-transmitted over the forward channel.

For the purposes of synchronization of the send and receive stations error-protection units, as well as regeneration of the incoming signals, the sub-multiplexing equipment is provided with a special correction device. The heart of the device is the send station clock pulse generator (CPG) with its output pulses recurring at a repetition frequency equal to the signalling speed used (600 or 1 200 pulses per second). The receive station extracts the clock (CLK) pulses from the demodulator output by means of a special clock pulse discriminator (CPD). The correction feature is characteristic of the majority

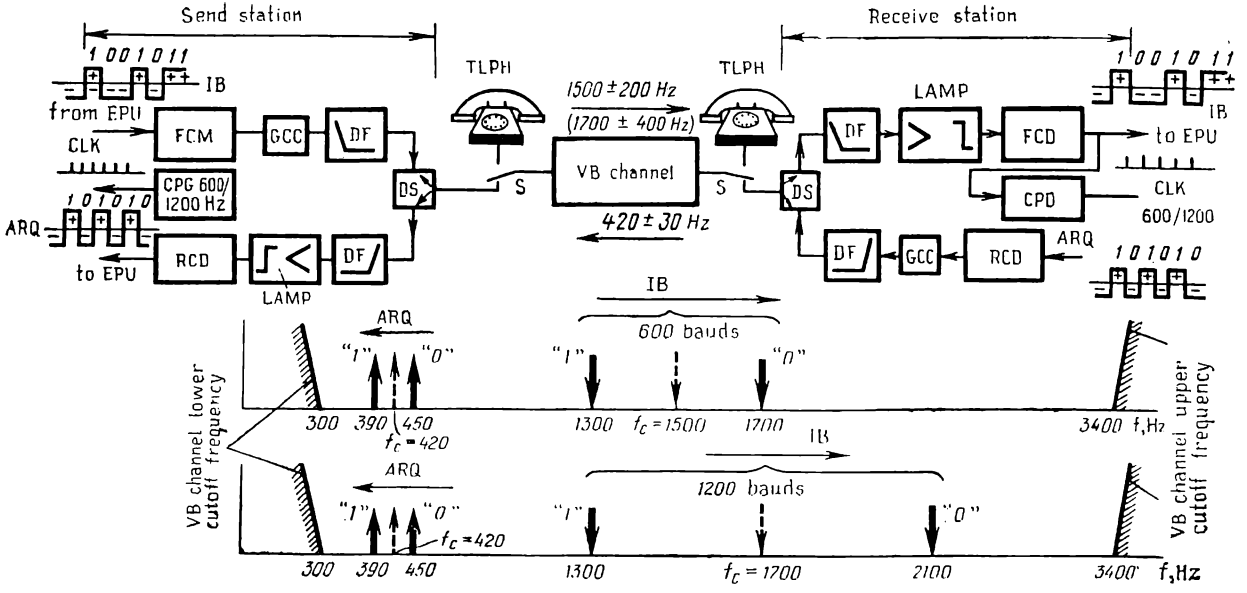

Send station
Receive station
1 0 0 1 0 1 1
IB
from EPU
CLK
FCM
GCC
DF
TLPH
1500 ± 200 Hz
(1700 ± 400 Hz)
TLPH
LAMP
FCD
to EPU
CPG 600/
1200 Hz
1 0 1 0 1 0
ARQ
DS
S
VB channel
S
DS
CPD
CLK
600/1200
RCD
to EPU
LAMP
420 ± 30 Hz
DF
GCC
RCD
ARQ
1 0 1 0 1 0
IB
600 bauds
ARQ
"1"
"0"
"1"
"0"
VB channel lower cutoff frequency
300
390
450
f_c = 420
1300
f_c = 1500
1700
3400 f,Hz
VB channel upper cutoff frequency
IB
1200 bauds
ARQ
"1"
"0"
"1"
"0"
f_c = 420
300
390
450
1300
f_c = 1700
2100
3400
f,Hz

Fig. 5.9

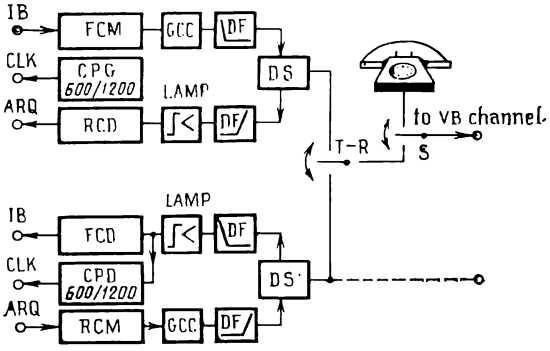


Fig. 5.10

of data transmission systems, although some are devoid of it (these rare systems are referred to as *incomplete*).

To provide a half-duplex capability, the send and receive stations are equipped with pairs of modulators and demodulators (one of each per forward and return channels). In half-duplex working, these modulator/demodulator pairs are alternated by the TRANSMIT-RECEIVE switch (*T-R* in Fig. 5.10). For a full-duplex operation over a four-wire non-switched communication link, an additional pair of wires is connected to the lower filter pair (dotted line in Fig. 5.10).

Full duplex is also possible with a two-wire VB link by multiplexing it into two sub-channels to allow the information to be transmitted in both directions simultaneously at a speed of 200 bauds. The operating frequencies are then 980 and 1 180 Hz for sub-channel *1* and 1 650 and 1 850 Hz for sub-channel *2*.

With FM, standard telephone links are (at least theoretically) capable of handling the information traffics at signalling speeds of up to 2 400 bauds. However, a high-speed working necessitates a thorough signal phasing, for already at a speed of 1 200 bauds the poor linearity of the telephone link phase-frequency characteristic tends to slow down the pulse rise and fall times, thus "smearing" the pulses and eventually impairing the information fidelity. This prompts designers to seek ways for ensuring an automatic correction of the frequency characteristics of telephone communication links.

Central control unit (CCU) serves as a tool ensuring the necessary interdependence of all other units and devices of the data transmission system, in order that the latter could most efficiently accomplish the following functions:

—input of data from the information source (a punched tape or a digital computer);

—segregation of the information intended for transmission into individual information blocks and introduction of cyclic-code check digits;

—feeding the data into the forward channel modulator;

—acceptance of the data from the forward channel demodulator;

—checking the received information block for errors;

—transmission of the ACK or ARQ auxiliary signals into the return channel modulator;

—extraction of the ACK and ARQ signals from the return channel demodulator;

—repeated transmission of the information blocks which the receive station EPU finds erroneous;

—generation of control and data interchange signals for the I/O devices and modems of the forward and return channels;

—output of data to the information user (a punched tape of digital computer);

—synchronization of the receive and send stations of the DTS in the initial phasing mode.

Use of data transmission systems in ADCS. The most expedient way of organizing transmission of the requisite operational information and TC, TR and BTC commands is through the use of a special-purpose ADCS management information sub-system built along multichannel PCM telecontrol equipment principles. The teleinformation processed by such a sub-system must be updated frequently enough to ensure a best possible functioning of the parent ADCS, as well as a timely and speedy correction of all likely power system abnormalities. It also seems practical that a separate DTS-type subsystem is provided within the ADCS to handle the production and statistical information and information related to scheduling the optimal values of operating condition parameters.

Together, these two sub-systems must constitute a united management information structure within a given ADCS, capable of a reliable and error-proof transmission of all the necessary information at all levels of the dispatch control hierarchy through a minimum of communication channels and facilities.

An intensive work is currently underway, both in the USSR and elsewhere, to design and construct, on a modern elementary basis, universal information transmission systems and facilities that would employ the concepts and principles of both the multichannel PCM telecontrol equipment and conventional data transmission systems for the transmission of large volumes of widely diversified information. These systems and facilities will most probably have a unitized construction allowing a considerable degree of flexibility in achieving a most efficient transmission of all the necessary types and volumes of information with the requisite speed, fidelity and accuracy.

5.5. Input, Storage and Processing of Teleinformation

The creation of an ADCS in power industry poses new and more stringent requirements regarding the quantity and quality of teleinformation related to the operating condition and status of the power system(s) and interconnections thereof. This is especially true of the telemetering of the basic condition parameters, and teleindication of the states of most important switchgear (such as circuit breakers, switches, etc.) that provide the basis for the construction of an information model of a given power net.

The need for a speedy analysis of the current state of affairs necessitates that a minimum amount of time be spent on reception and processing of a large number of various measurands. It is becoming increasingly clear that a successful solution of this problem is hardly possible except through the use of digital computers, although computerization does bring with it problems of its own, especially as regards organization of the input, storage and processing of TM and TI data.

The experience gained in the use of various telecontrol facilities in power industry indicates that in terms of the requisite number and information handling capacity of communication channels and accuracy and fidelity of the transmitted information, most effective (and therefore most popular) turn out to be multichannel PCM telecontrol systems of the type similar to the Soviet-made STIMUL and MKT systems. For this reason, this section will mainly focus on the input to, storage in, and processing by ADCS computers of the teleinformation handled by these (and similar) telecontrol systems.

Teleinformation Input and Processing. Any TM or TI teleinformation intended for input into an electronic digital computer must, in addition to the information message (i.e., the TM or TI measurand proper), contain certain auxiliary "flags" that together form what is known as "identifier". The flags making up the identifier may vary from one application to the next, but whatever the application they must always provide an unambiguous identification of the type and source of the teleinformation in question. In most cases, the source (address) of the incoming teleinformation is identified by the number of the associated telecontrol device and the number of a given message within the transmission cycle of that device. In the case of TI messages, one more flag is required to identify the number of the position (digit) within the message.

As an example, consider Fig. 5.11 showing a sample identifier/message combination for a situation when the digital computer is interfaced with two groups of telecontrol devices, of which one consists of the MKT type devices, and the other of the STIMUL type devices.

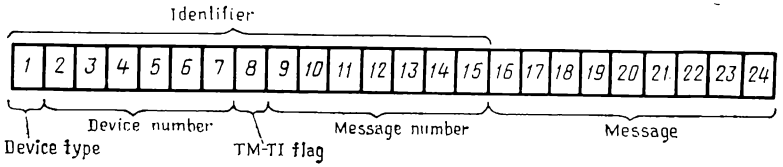


Fig. 5.11

Now, digit *1* of the identifier is used to indicate the type of the telecontrol device. Let us assume that a 0 in that digit corresponds to a type MKT device, and a 1 implies a type STIMUL device. Digits *2* through *7* are put aside for encoding the device number, which allows up to 64 telecontrol devices of each type to be polled. Digit *8* is employed as the flag of the type of the incoming teleinformation (TM or TI). Binary digits *9* through *15* help define the message number within the transmission cycle. Finaly, the last nine binary digits (*16* through *24*) constitute the message proper.

The discrete nature of the transmitted teleinformation strongly influences the way its input into a computer is organized.

The message codes available from the output register of the telecontrol system receive station alternate at a rate determined by the rate of transmission and number of the binary digits employed to convey each single message, such that

$$t_0 = \gamma' n v^{-1} \tag{5.15}$$

where t_0 is the time during which the output register stores a given message (otherwise known as "data-ready" time), seconds; $\gamma' > 1$ is the redundancy factor, conditioned by the number of extra information validity check digits; n is the number of binary digits used to convey a given message; v is the rate of transmission, bits per second.

The multichannel PCM telecontrol devices interfaced with the ACDS computer usually differ in their information capacity (the number of messages transmitted) and transmission rate, and are thus characterized by various data-ready times. Besides, the telecontrol devices are, in the general case, operating asynchronously. Therefore the data-ready time of the polled devices varies within broad limits (from $t_{0\min}$ to $t_{0\max}$). With the computer-interfaced telecontrol devices polled sequentially (cyclically), the time for polling all the devices should not exceed the maximum data-ready time, such that

$$t_{poll} \leqslant t_{0\min}, \tag{5.16}$$

for otherwise the messages whose data-ready time is shorter than the polling cycle will not be polled and will be liable to be lost. On the

other hand, the devices whose data-ready time is longer than the poll cycle duration will be polled more than once, thereby introducing an unnecessary redundancy to the input information. A need therefore arises to so organize the polling of all the telecontrol devices that each of them would be polled only once during its data-ready time.

Most simply, such a one-time acceptance of the incoming messages can be realized with the aid of a circuit generating a special "data-ready" signal each time a fresh message is entered into the telecontrol system output register to allow this message to be read therefrom into the computer memory. In the simplest case, such a read-enable circuit can be an array of a total of n coincidence (AND) gates, with the "data-ready" signal applied to one of the inputs of each of them, the other inputs being coupled to the respective outputs of the telecontrol device output register. The "data-ready" signal is cancelled once a given message has been copied into the computer memory. As a result, no "data-ready" signal will be pending during subsequent polling cycles, and the same message will not be repeatedly entered into the computer. Thus, readout of data from the output register is disabled until the next message is entered into it and a fresh "data-ready" signal is generated.

In the way of an example, consider a situation when information collected from a total of 45 telecontrol devices whose characteristics are listed in Table 5.3 needs to be read out.

Table 5.5

Device group number	Device type	Transmission rate, bit/s	Number of binary digits in each message, n	Redundancy factor, γ'	Number of devices
1	STIMUL	100	9	2.0	10
2	STIMUL	50	9	2.0	10
3	MKT	160	7	1.71	20
4	MKT	80	7	1.71	5

Let us first apply Eq. (5.15) to find the "data-ready" time for each telecontrol device group

$$t_{01} = \frac{2 \times 9}{100} = 0.18 \text{ s}; \quad t_{02} = \frac{2 \times 9}{50} = 0.36 \text{ s};$$

$$t_{03} = \frac{1.71 \times 7}{160} = 0.075 \text{ s}; \quad t_{04} = \frac{1.71 \times 7}{80} = 0.15 \text{ s}$$

Thus, according to Eq. (5.16), the polling time for all the 45 telecontrol devices in question should be shorter than 0.075 s.

Now, practical implementation of the input, storage and preliminary processing of the teleinformation will to a considerable degree be conditioned by the logical structure and capabilities of the computer used.

If each incoming message is accepted for processing immediately upon arrival and its processing is accomplished sooner than the pause between two successive arrivals is over, then only one memory location will be sufficient to accommodate all the incoming messages (because the relevant information will then be written into it in a purely sequential manner). Under such conditions, the time chart of the computer operating cycle can be thought of as consisting of the following sequence of operations:

—coupling the computer-to-device interface commutator to the output register of the currently polled receive station;

—filling the address register with the address of the computer main memory location allocated for the incoming message;

—storing the input message in the computer memory at the above address;

—initiation of the program controlling the preliminary processing of the received message;

—polling of the next-in-line telecontrol system station.

The preliminary processing of teleinformation implies execution of the following operations:

—checking the incoming teleinformation for validity;

—generation of signals warning the dispatcher that the state of the monitored equipment has changed;

—checking the basic operating condition parameters for compliance with their respective ratings and signalling the dispatcher of any abnormalities;

—generation of an information model of the monitored power net;

—computation of the generalized characteristics of the power system operating conditions essential for a successful solution of managerial and planning problems.

It is quite apparent that the time spent on the execution of the above operations must never exceed the time elapsing between the polling of two successive telecontrol devices in order that the following condition would hold true

$$t_{poll} \geqslant N_1 K/\lambda \tag{5.17}$$

where N_1 is the average number of machine operations required to input, store and pre-process a single message; K is the equivalent number of the telecontrol devices being polled; λ is the average computer speed, expressed as the number of operations it performs per second.

The equivalent number of polled devices is given by

$$K = t_{0\,\min} \sum_{i=1}^{k} \frac{1}{t_{0i}} \tag{5.18}$$

where $t_{0\min}$ is the minimum "data-ready" time for the polled telecontrol devices, seconds; k is the number of telecontrol devices actually interfaced with the computer; t_{0i} is the "data-ready" time for the i-th telecontrol device, seconds.

Considering that apart from the input and pre-processing operations the computer must perform a number of other dispatch functions, Eq. (5.17) takes on the following form

$$t_{poll} \geqslant N_1 K/\lambda + t_s \tag{5.19}$$

where t_s is the computer time required for the solution, during each polling cycle, of the dispatch problems not directly related to the input and pre-processing of the teleinformation.

If we assume that $t_s = \alpha t_{poll}$ (with α being a unity-fraction coefficient), then the average computer throughput will be expressed as

$$\lambda = N_1 K/[(1-\alpha)\, t_{poll}] \tag{5.20}$$

It must be clear by now that the teleinformation input and processing organized as outlined above can hardly permit an efficient utilization of the computer capabilities, because multiple auxiliary program transfers and jumps are required to process each single message. Therefore for the majority of applications the most practical way of handling the teleinformation is batched input and processing.

With batched processing, only a fraction of the auxiliary operations will have to be executed with each message. Specifically, the incoming teleinformation can be accepted to a low-speed simplified processor that would perform the elementary operations of addressing and sending the incoming messages into the main memory. In third-generation computer systems these functions are standardly performed by the so-called channel processor, while other functions (such as processing of the teleinformation and solution of other ADCS problems) are entrusted with a multi-purpose powerful central processing unit that has at its disposal a flexible instruction repertoire and a highly developed priority interrupt system.

With such a computer structure, the organization of a multi-program computational process must comply with the following time restrictions

$$t_1 - t_2 = \alpha t_1; \quad t_1 + t_2 = t_3 \tag{5.21}$$

where t_1 is the time spent by the channel processor for the input of a single information batch (array), s; t_2 is the time spent by the cen-

tral processing unit on the preliminary processing of the teleinformation batch accepted during t_1, s; α is a coefficient indicating what part of the overall machine time the central processing unit stays busy solving problems not directly related to the preliminary processing of the teleinformation, fractions of unity; t_3 is the maximum admissible delay between the acceptance of an individual message and completion of its preliminary processing, s.

For further analysis, let us introduce the concept of the estimated rate of arrival of teleinformation to the computer

$$C = K/t_{0\min} \tag{5.22}$$

where $t_{0\min}$ is the minimum "data-ready" time for the polled telecontrol devices.

Solving the system of equations (5.21) for t_1 and t_2, we have

$$t_1 = t_3/(2 - \alpha);\ t_2 = t_3(1 - \alpha)/(2 - \alpha) \tag{5.23}$$

The quantity of messages accepted by the channel processor during t_1 we shall denote as Q. Apparently, this must be equal to the number of messages which the central processing unit processes during t_2. Equating the Q quantities expressed through t_1 and t_2, we can write

$$Ct_3/(2-\alpha) = \lambda t_3(1-\alpha)/[N_2(2-\alpha)] \tag{5.24}$$

Solving the above expression for λ, we come to the conclusion that the requisite average throughput of the central processing unit must be

$$\lambda = CN_2/(1 - \alpha) \tag{5.25}$$

The most expedient teleinformation array size processed by the central processing unit during each access to the preliminary processing program will then be given by

$$Q = Ct_3/(2 - \alpha) \tag{5.26}$$

In Eqs. (5.24) and (5.25), the term N_2 denotes the average number of machine operations which the central processing unit spends on the preliminary processing of each input message. We can write that

$$\theta = N_2/N_1 \tag{5.27}$$

where θ is a coefficient (expressed in fractions of a unity) that shows how N_2 measures against the overall number of operations performed in a one-processor computer system for the input and processing of one message, N_1.

Recalling that the most expedient polling cycle duration for all the telecontrol devices interfaced with the computer equals the minimum "data-ready" time, Eq. (5.20) can be re-written as

$$\lambda = CN_1/(1 - \alpha) \tag{5.28}$$

Comparison of Eqs. (5.25) and (5.28) leads one to the conclusion that the requisite throughput of a multi-processor computer system central processing unit can be θ times as small as that of the computer that both accepts and pre-processes the teleinformation.

The overall capacity of the multi-processor computer system main memory allocated for storing the incoming teleinformation must be equal to $2Q$, with all current teleinformation being stored in a main memory segment of capacity Q and the earlier accepted data array of the same size being processed by the central processing unit.

Storage of teleinformation. In a situation where the machine word format coincides with the format of the messages, the requisite channel processor speed must meet the condition

$$\lambda_{ch} \geqslant C\,(N_1 - N_2)$$

Otherwise, this speed must be

$$\lambda_{ch} = \beta C\,(N_1 - N_2)$$

where β is a coefficient (measuring fractions of a unity) expressing the ratio of the length of the message (together with its identifier) to the length of the standard computer word.

Most simple to realize is the strictly sequential ("as it comes") teleinformation storage principle, when each individual message together with its identifier is written into a main storage location whose address is dependent on the time of that message arrival to the computer-to-device interface. In this arrangement, the computer address register functions as a counter whose contents is incremented by unity each time a new message is written in. The main memory area allocated for the teleinformation is altered by modifying the origin address entered into the computer address register.

There exists also the so-called ordered method of storing the teleinformation, whereby the address of the main memory location allocated for the input message is determined by the value of the corresponding identifier. Each of the messages arriving to the computer input can then be written to only a strictly definite and rigidly allocated memory location whose address is given by

$$A_i = A_0 \bigwedge I_i \tag{5.29}$$

where A_0 is the origin address of the main memory area allocated for the incoming teleinformation. This address is conditioned by the state of q most-significant digits of the computer address register; $\bigwedge$ denotes logical addition; I_i is the value of the identifier of each i-th message.

The number of the most-significant binary digits in the computer address register taken up by the origin address A_0 equals

$$q = a - z \tag{5.30}$$

where a is the overall number of the address register digits; z is the number of binary digits needed to accommodate the message identifier.

A clear-cut advantage of the ordered storage method is a more efficient use of the available computer memory, since the latter needs only to store the messages proper with no accompanying attributes or flags. The achievable economy is in direct proportion to the length of the message identifiers which, with the sequential approach, are stored together with associated messages.

Yet, with the ordered storage of messages the available computer memory will hardly be used at top efficiency unless the number of the telecontrol devices polled and the number of messages within the transmission cycle of each individual device are coincident with one of the binary series numbers, and all the telecontrol devices transmit an equal amount of messages, i.e. have an equal information capacity. If telecontrol devices are operating synchronously at an equal transmission rate, then the number of messages arriving to the computer per one teleinformation updating cycle can be defined as

$$N = kr = 2^x 2^y \tag{5.31}$$

where k is the number of multichannel PCM telecontrol devices interfaced with the computer; r is the number of messages within one transmission cycle (equal for all the telecontrol devices polled); x, y is the number of binary digits making up the binary code of, respectively, the device number and the message number within one transmission cycle of each device.

The case when all the telecontrol devices interfaced with the computer would have an equal information capacity is hardly conceivable, because various amounts of information need to be telemetered from various ADCS power installations. To ensure a best possible utilization of the computer memory under such conditions, resort can be had to an artificial levelling of the information capacity of the polled telecontrol devices by assigning one and the same number to two or more sequentially polled devices.

If the ADCS computer has a variable-length word structure, a more or less efficient utilization of all the digits of the available main memory addresses can be achieved through the use of addressable operands of a length identical or roughly approximate to the format of the incoming teleinformation. Otherwise, two or more messages will have to be written into one and the same main memory location, in order that the unused part of the operand digits would have a minimum length.

With the teleinformation stored sequentially, one and the same memory location can be used to store sequentially arriving messages characterizing different measurands. On the other hand, the ordered storage method allows one and the same main memory location to be

employed to sequentially store different values of one and the same measurand.

If the teleinformation is transmitted by telecontrol devices operating asynchronously at different transmission rates, application of the ordered storage technique necessitates such a processing of the incoming messages that would totally preclude a loss of information by having two or more successive values of a measurand written into one and the same digits of the assigned main memory location.

One of possible ways of achieving this is to restrict the admissible amount of time during which an array of teleinformation accepted for processing as a batch is formed. This time must be shorter than the minimum teleinformation updating cycle of the telecontrol devices interfaced with the computer, such that

$$\tau < T_{0\min} \tag{5.32}$$

where τ is the time needed to form the teleinformation array, equal to the time between two successive runs of the message processing program; $T_{0\min}$ is the shortest updating cycle of the telecontrol devices interfaced with the computer.

A teleinformation updating cycle can be defined as the time interval between two successive arrivals to the receive station of one and the same cyclically transmitted measurand, and is given by

$$T_{0\,i} = t_{tr\,i} r_i + n_{sync\,i} v_i^{-1} \tag{5.33}$$

where $t_{tr\,i}$ is the time needed for the i-th device to transmit a single message. In most practical applications, this is almost coincident with the "data-ready" time; r_i is the information capacity of the i-th telecontrol device, equal to the number of messages per transmission cycle; $n_{sync\,i}$ is the number of the synchronization signals (length of the sync train) transmitted by the i-th telecontrol device in the beginning of every transmission cycle.

Another solution of the same problem consists in that the current values of a given measurand are stored at a fixed address, successively filling up the word (operand) digits allocated to it, with the first-in message occupying, say, the least significant digits, and the last-in message occupying the most-significant digits. The number of messages written in a given addressable operand designed to hold the values of the i-th measurand, is found as

$$m_i = \tau / T_{0i}$$

The length of each such operand (i.e., the number of binary digits used) must not exceed the maximum addressable word format in order that the following condition would hold true

$$l \geqslant q\tau / T_{0i}$$

where l is the maximum number of binary digits of the addressable operand; q is the number of binary digits occupied by each of the measurand values.

With either approach, the size of the main memory area allocated for storing the incoming messages (in terms of the main memory addresses) remains the same, equal to 2^z, with z being the number of binary digits occupied by the message identifier. However, in the former case all the addressable operands contain an equal number of binary digits, whereas in the latter case the operands vary in their format, and the number of binary digits they contain is in inverse proportion to the teleinformation updating cycle. Therefore with the number of addressable words being the same, the former method requires fewer main memory digits. The achievable economy turns out to be directly proportional to the difference between the maximum and minimum updating cycles with which the teleinformation is being transmitted.

In multichannel PCM telecontrol systems of the STIMUL type, TM information is normally transmitted on a cyclic basis, while TI messages are transmitted spontaneously, either on request from the dispatch control center or as an event information.

In the latter case the send station transmits the necessary group of TI messages immediately after completion of the current TI message, and proceeds to cyclically transmit TI and TM until either a positive acknowledge signal arrives over the return channel or the request for the TI transmission is cancelled to allow a given telecontrol device to resume a cyclic transmission of TM information only. It thus follows that in the spontaneous transmission mode the teleinformation updating cycle may vary between T'_{0i} and T''_{0i} (with T'_{0i} being the updating cycle during transmission of the TM messages only, and T''_{0i} being the updating cycle during TM and TI transmissions). Under such conditions the maximum amount of time allowed for forming a teleinformation array intended for processing as a batch must be

$$\tau \leqslant T'_{0\,\min} l/q \tag{5.34}$$

where $T_{0\min}$ is the TM teleinformation updating cycle minimum for all the telecontrol devices interfaced with the computer.

It may thus be concluded that from the point of view of main memory requirements the ordered method of storing the teleinformation offers greater advantages. The net effect is greatest when the teleinformation is transmitted in a binary code format by multichannel PCM telecontrol devices whose information capacities are compatible with the binary distribution series.

In the USSR, automated dispatch control systems of many hierarchy levels (power-system, area-level control boards and united power grid central control department) make an extensive use of small

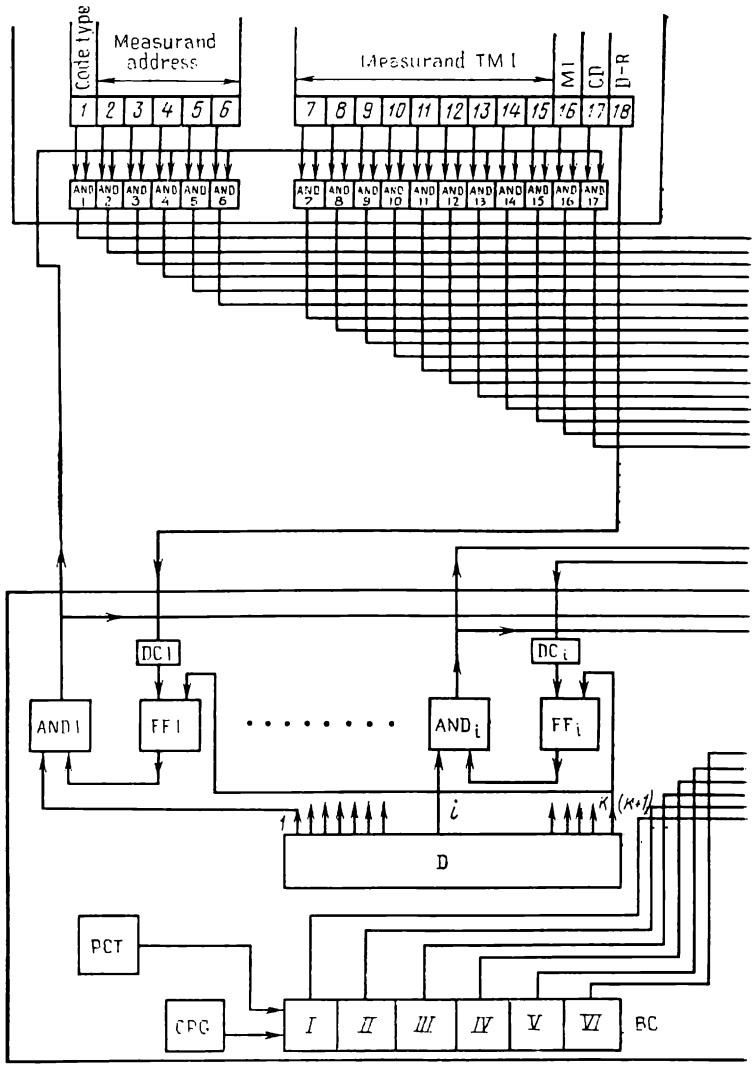


Fig. 5.12

computers with appropriate software support to ensure reception, input, processing, output, recording and display of all necessary information and data. Specifically, they:

1. Input current (instantaneous) TM and TI measurands.
2. Check the incoming teleinformation for validity and warn the

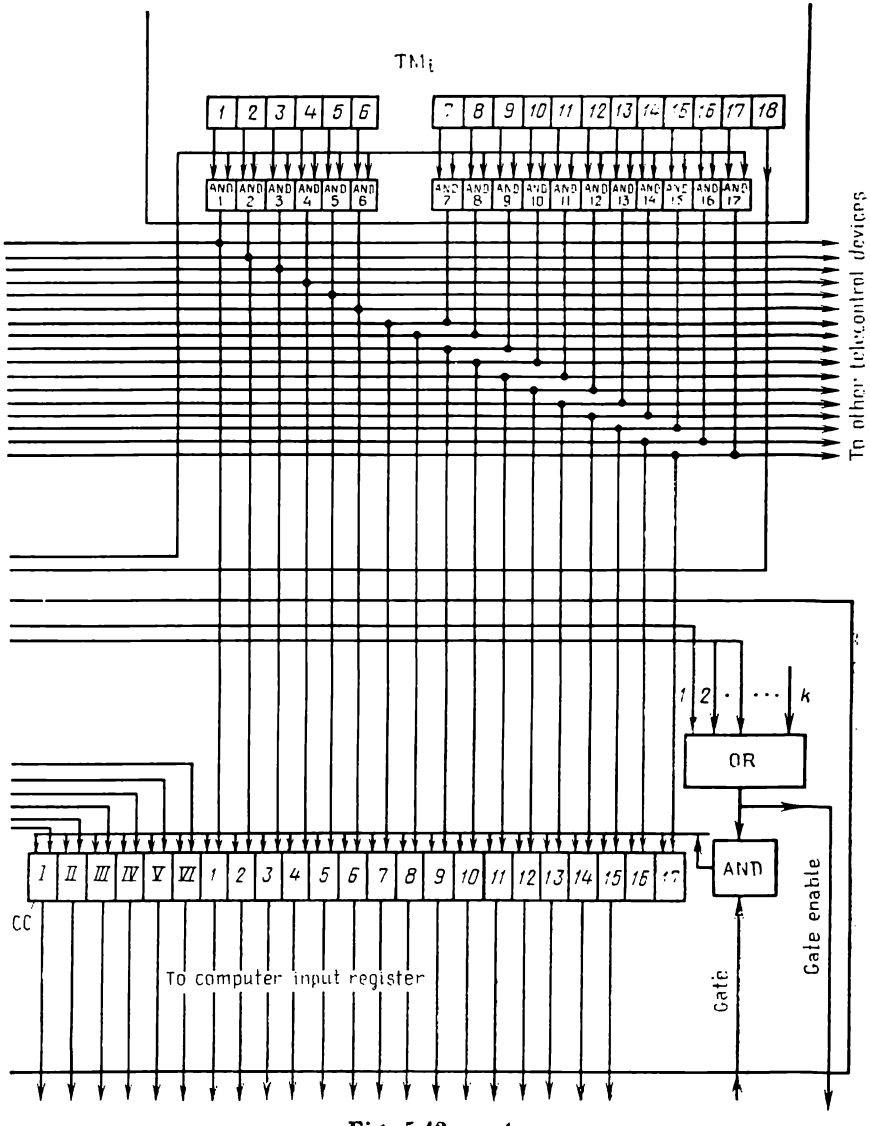


Fig. 5.12, cont.

user of errors and measurand abnormalities, as well as find averaged values of the monitored measurands by utilizing the "moving average" principle and recurrent relations. This permits adequate rejection of noise and random incursions of the measurands. Monitoring of all TI events and measurand abnormalities helps to analyze emergency

situations and yileds certain quantitative criteria for assessing the quality of control over the values of voltage, frequency and inter-system power exchanges. One example are the histograms depicting distribution of the monitored measurands deviations from their ratings over a definite period of time.

3. File the processed teleinformation arrays (including abnormal TM and TI measurands), and compute certain generalized indices (such as power interchange totals, overall power generation, etc.). These abnormal TM and TI files are stored in a format allowing the user to consecutively follow the progress of emergency situations over a sufficiently protracted period of time. The processed and filed teleinformation and data arrays are also instrumental in prognostication and modelling of certain operating conditions.

4. Represent the monitored teleinformation by means of appropriate meters, annunciators and indicators (automatically) or display it on CRT indicators and monitors (upon the operator or dispatcher request). In the latter case, the displayed TM and TI measurands are regularly updated. A conversational mode capability is also possible through the use of the functional keyboards of the CRT displays giving the operator access to a sufficiently developed system of computer instructions.

5. Display, upon the user request, a wide range of statistical, production, reference, instructional and suchlike information on CRT monitors.

6. Monitor the functioning of all the system hardware and software.

Schematic diagram of teleinformation input device (Fig. 5.12). The device incorporates:

—a polling cycle transducer (PCT) that determines the time interval between successive pollings;

—a clock pulse generator (CPG);

—a binary counter (BC) determining the address of the telecontrol device being polled;

—an address decoder (D) that has as many outputs as there are polled telecontrol devices plus one;

—coincidence circuits (CC) equal in number to the binary digits of the code word written into the computer memory;

—flip-flops (FF1 through FF_i);

—differentiating circuits (DC1 through DC_i);

—AND circuits (AND1 through AND_i) equal in number to the telecontrol devices being polled;

—an OR circuit;

—AND circuits accepting the outputs from the CC coincidence circuits every time the computer sends in a gate pulse.

Initially, the polling cycle transducer resets to zero the binary counter to which the clock pulses are applied. This zero state of the

binary counter signifies the commencement of a fresh polling cycle. If a total of k telecontrol devices are to be polled, the transducer must put out one pulse after every $(k + 1)$ clock pulses, which means that the clock pulses generator output frequency should be $(k + 1)$ times as high as that of the transducer.

During each transducer cycle, one of the decoder outputs produces a signal coupled to the coincidence circuit of the associated telecontrol device. Since the coincidence circuits are simultaneously driven by the counter binary code signal, the result is the code of the number of the telecontrol device being currently polled. If the decoder signal arrives at a time when the flip-flop of the corresponding device happens to be in a 1 state, the coincidence circuit will put out a pulse allowing that device to be polled. The device will thus read in the address code of the measurand conditioned by the number of the incoming message within the transmission cycle of the polled device.

As shown in the diagram of Fig. 5.12, the measurand address corresponds to the states of flip-flops *2* through *6* of the polled device output register. Read in simultaneously will be the contents of flip-flops *7* through *17* of the same device. The first flip-flop will contain the information determining the type of the code employed for transmission of a given message (binary or binary-coded-decimal). Flip-flops *7* through *15* will contain the message (measurand) proper, flip-flop *16* will signal the message type (TM or IT), while the contents of flip-flop *17* will be used to write in the information check digit.

Each of the flip-flops is set to 1 by the associated differentiating circuit driven by the "data-ready" (D-R) signal produced by the telecontrol device upon the arrival of each next message (provided that the latter has not been found corrupt).

All the flip-flops are reset simultaneously after all the telecontrol devices have been polled, i.e. in the last $(k + 1)$-th cycle of the decoder and before the binary counter is again reset to the 0 state.

Thus, if a given telecontrol device accepts no new message by the time the next polling cycle commences, the flip-flop reset to zero in the end of the previous cycle will disable the associated coincidence circuit, thereby preventing the information from being read into the computer memory.

As indicated in the diagram of Fig. 5.12, the information is entered into the computer memory in the form of code words containing 23 binary digits. The first six digits of each code word, marked with Roman numerals (see the CC boxes), condition the number of the telecontrol device from which teleinformation has been read into the computer memory.

The teleinformation is entered into the computer in response to a special "gate" signal generated each time one of the k inputs of the

OR gate accepts a signal signifying that a fresh (previously unrecorded) information is pending.

With ordered storage, the address of the computer memory location allocated for storing the input message is determined by the information arriving to the computer from the first 12 coincidence circuits. The message proper, together with its type and parity attributes, enters the computer memory for further processing from the coincidence circuits numbered 7 through 17 in the diagram of Fig. 5.12. With sequential teleinformation storage, the address register of the computer operates as a counter incremented by each "gate enable" signal.

REVIEW QUESTIONS

1. Define the modulation methods used for transmission of discrete signals and give their comparative characteristics.
2. Define switched and non-switched communication links and describe their potential applications.
3. Give a comparative characteristic of the cyclic and spontaneous methods of information transmission.
4. Draw a simplified block-diagram of a multichannel PCM telecontrol device.
5. In what way is teleinformation transmission with various updating cycles beneficial?
6. How can you define the static and dynamic components of the overall telemetering error?
7. Describe uses of multi-step commutation in teleinformation transmission.
8. How do the transmission rate and updating cycle relate to each other?
9. What methods can be applied to improve fidelity of transmitted teleinformation?
10. Draw a block diagram of a data transmission system.
11. Describe the purpose and operating principle of the error protection unit.
12. Give a comparative analysis of the error control techniques utilized in data transmission and telecontrol systems.
13. Define functions of the return channel in a data transmission system.
14. Draw a schematic diagram of the teleinformation input device.
15. Name and describe the methods that can be used to store teleinformation in computer memory.

Chapter 6

Analog Computers and Their Application in Power Industry

6.1. General

Historically, analog computers are one of the oldest known types of computing devices. The growth and development of analog computer technology has kept abreast of the advances in electrical and power engineering, contributing greatly to the progress in these fields.

At the present time, analog computing techniques are increasingly combined with digital methods of data processing, giving rise to the creation of hybrid computers (having the features of both the analog and digital computers) which should find wide application in the power industry. Assuming that the reader has a background knowledge of analog computers and their use, the following discussion will be confined to third-generation analog computers and their practical implementation in dispatch control.

As it will be recalled, *analog computers* are those computers whose operating principle is based on the analogy between mathematical descriptions (equations) of the systems of different physical nature. The creation of such analogs makes it possible to replace the original (natural) system by an artificial system which lends itself more readily to investigation and has analogous mathematical relations, and then to analyze the artificial system and to apply the obtained results to the original system. The simile between the natural and artificial systems is established by comparing their mathematical descriptions. This method has come to be known as a *method of mathematical analogs*. In early analog systems, the variables in a problem were represented by certain analogous physical quantities, i.e. had a continuous representation, so that the term "analog" has come to be associated with continuous representation of data.

Continuous representation of information is not the sole means of mathematical modelling insofar as mathematical models of various structures can be created by digital methods. The difference between the continuous (analog) and discrete (digital) forms of information

representation boils down to the different input/output and processing capabilities. Therefore, the distinguishing features of the analog and digital computers lie in the processing structures employed.

The first analog systems which appeared at the turn of this century following the creation of mathematical descriptions for a number of important physical and technical systems were essentially experimental tools in which the quantities (variables) under investigation were of the same physical nature as in the original system. Accordingly, voltages in the networks analysers were simulated by the voltages of other magnitude, as were the currents, etc. However, there was frequently no similarity between the elements as compared to physical models. For instance, power lines were represented by inductance coils or even resistors.

The next step was the development of *indirect-analogy models* in which the current passing through a capacitor could represent, say, the velocity of a moving body and the amount of charge of this capacitor, the path travelled by the body, etc. This approach has greatly expanded the range of applications of such models and proved to be of major importance in cases where the variables were not suitable for convenient investigation. They were used in such applications as simulation of mechanical stresses in structural elements, etc. The use of the indirect-analogy models was an important step in the development of mathematical models in general and in their implementation as computing models.

Computing models. One of the first computing models based on the method of mathematical modelling were the so-called *a.c. and d.c. network analyzers*, used in the design and operation of power systems to the present day. It should be noted that the structure of the computing models, which are basically direct-analogy models, differs greatly from that of the original system, that being so because the original system deals with three-phase currents and voltages, and the model has a single-phase setup. This called for the use of a special method, known as a symmetrical component method, in the investigation of the asymmetrical operating conditions of the systems.

The computing models found wide application in other fields of science and technology with a specialized approach taken in selecting an analog for a particular original system. The demand for increased versatility stimulated the production of devices with predetermined physical properties corresponding to a definite mathematical operator (such as integrators, differentiators, etc.). These devices, commonly called *computing*, are the building blocks of modern analog computers.

Computing elements. Operation of the computing elements of analog computers can be based on different principles, such as electrical, kinematic (mechanical), hydraulic, pneumatic, and also combinations of these, such as electromechanical, hydroelectric, etc.

It should be noted that the desirable operating properties of the elements were emphasized at the expense of unwanted, or spurious, characteristics (i.e. those that did not conform to the requirements of a particular application). This called for the use of active elements in the form of amplifiers with output feedback. The obvious choice were the electronic d.c. amplifiers with negative voltage feedback, commonly known as *operational amplifiers*. These amplifiers form the basis of modern analog computers.

Analog computers are made up of elements consisting of operational amplifiers and associated circuitry including resistors, capacitors and (if required) diodes. The combination of these components makes it possible to obtain both linear and nonlinear operators, with the accuracy and stability of operations performed by these operators determined by the quality of the components themselves.

Recent years saw the appearance of semiconductor as well as microelectronic operational amplifiers based on integrated and hybrid integrated circuits, obsoleting the tube amplifiers.

Substantial changes have been made in the circuit design of operational amplifiers. These include: (1) increased accuracy and stability of capacitors and resistors (their accuracies are now measured by the hundredths and even thousandths of per cent); (2) the use of miniaturized relays that can be directly incorporated in the printed circuitry; (3) the use of microelectronic diode-resistor matrices in function generators.

As a result, the operational amplifiers have become more compact and gained in stability, and the accuracy of four decimal places is now a standard. A comparative study of analog and digital computers shows that with the advent of new technology, the complexity and cost of computer elements and assemblies change but little. In analog computers, however, the total cost of the machine is more dependent on the cost of its components (patch panels, coefficient-setting electromechanical systems, etc.).

The basic function of an operational amplifier is to provide an output signal which is a function of its input, and this is more difficult to attain than with discrete elements where a step-like change is required. That is why the semiconductor and integrated-circuit versions of such circuits (known as linear in microelectronic practice) are sometimes not even nearly as cost-effective as discrete circuits. Another important consideration is that the analog computer downtime is generally higher as compared to digital computers, since it is more difficult to effectively use the analog computers on a time-sharing basis. As a result, the comparative characteristics of analog computers have degraded with respect to digital computers with the appearance of the third generation of digital computers. Moreover, the use of high-speed digital computers has opened up new ways for a complex approach to the solution of problems.

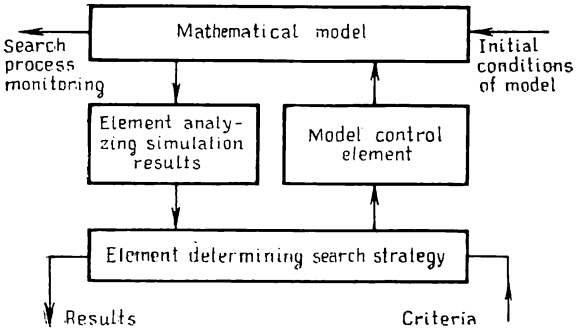


Fig. 6.1

All computing aids based on the principle of mathematical modelling are intended to predict (forecast) the behaviour of the object under investigation being influenced by various external factors (loads, disturbances, etc.). So, the investigation of a power system may involve a flow analysis under steady-state conditions and the determination of state variables under transient conditions. At the same time, it may become necessary, at the design or operation stage, to analyze the obtained results, check them for compliance with the tolerance or optimality criteria, and to plan for future changes in the structure, parameters and operating conditions of the system in order to achieve the desired relationship, i.e. to synthesize the system proceeding from the specified conditions.

Such synthesis cannot be accomplished without search, and the strategy of this search is the subject of mathematical programming. We are concerned here only with the technical means for its implementation. Referring to Fig. 6.1, there are four basic elements involved in the solution of this type of problems, namely a mathematical model of the system, an element controlling the condition of this model, an element analyzing the results of simulation, and an element which determines the strategy of search.

The relations between these elements can be easily illustrated by taking a simple problem with the aim to determine the limits of transient stability of a transmission system. By simulating the transient processes, the system establishes the initial load and introduces the desired disturbances with the aid of the control element. The analyzing element determines the nature of the resultant dynamic transfer ("stable"—"unstable"), while the element determining the strategy of search gradually increases the transmission load until the nature of transfer is changed as evidenced by the analyzing element.

In fact, it is not important for an engineer using the computer (computer user) which way one or another element is realized.

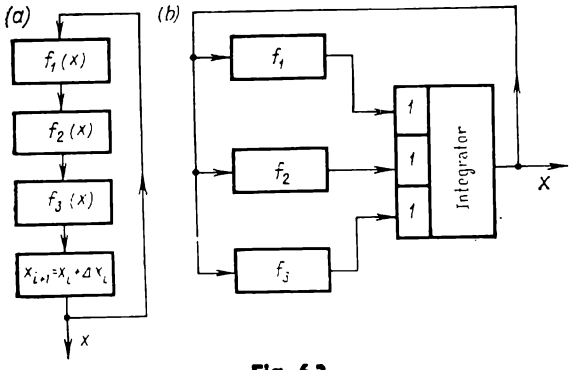


Fig. 6.2

A computer must meet the needs of the user from the standpoint of speed, accuracy and cost-effectiveness. At the early stage of computer development, analog computers played a dominant role in the process of mathematical modelling, while the search process was automated by using additional automatic optimizers which for the most part employed electromechanical relays. However, their logical capabilities were limited and the optimizers were later successfully replaced by digital computers. This trend can also be traced in the development of mathematical models as a whole. This approach brings about substantial changes in the operating characteristics, though it is not feasible in all cases.

By comparing the analog and digital computers, it was earlier upheld that analog computers have a higher speed though less accurate, while digital computers, on the other hand, have lower speed at higher accuracy. To a certain extent, these concepts hold true to the present day, although the speed of digital computers has increased as has the accuracy of analog computers due to the progress made in the analog and digital computer technology. Today, the former differences are not so important as the differences in the machine structure and the organization of computing process.

In a digital computer, the computations are performed in a sequential manner, i.e. information is processed by steps. Concurrent execution of operations by the elements operating in parallel can be employed only if absolutely necessary. By contrast, in an analog computer each operation is executed by a definite element operating simultaneously with other elements (parallel operation).

This can be exemplified by referring to the diagram in Fig. 6.2 which illustrates the solution of an ordinary differential equation $\dot{x} = f_1(x) + f_2(x) + f_3(x)$. This is a first-order equation whose right-hand side contains several arbitrary functions x. When comparing the sequential (Fig. 6.2*a*) and parallel (Fig. 6.2*b*) solutions, it

should be borne in mind that the differences between them lie not only in the method of integration, but also in the order of computation of their right-hand sides. A digital computer calculates them in a sequence of steps and an analog one does it simultaneously. In this way, the problem will be solved faster on the analog computer even provided that the computers have the same computing speed. However, if the number of specified $f(x)$ should exceed the number of computing elements available for this purpose, it would be impossible to solve the problem on the analog computer whereas in the case of the digital computer this would only result in the increased computing time.

Similar situations arise during solution of many problems, underlining the properties of the processing structures rather than the properties of the forms of information representation. Briefly, these properties can be summarized as follows:

Parallel structures
The computing process is coincident in time and distributed in space. An increased size of the system being simulated leads to an increase in the amount of hardware required without affecting the simulation time.

Sequential structures
The computing process is coincident in space and distributed in time. An increased size of the system being simulated leads to an increase in the simulation time with the hardware remaining practically unchanged.

As a result, the parallel structures which are flexible enough for problem solution become increasingly "rigid" as the scope of the problems expands. The sequential structures, on the other hand, overcome the existing limitations and can be easily adapted to conform to the nature of the system. This disparity is primarily due to the growing number of computing operations. Given the various and frequently changing problems, the difference in the computing time inherent in the parallel and sequential structures can be minimized due to the increased speed of execution. But a substantial increase in the computing time of digital computers involved a number of changes connected with the implementation of the principle of parallel operation in all its forms, i.e. from the organization of several input/output information streams up to the conversion to purely parallel structures, giving rise to certain difficulties. In this connection, the following possibilities have emerged:

(1) use can be made of combinations of processors made in the form of microcomputers;

(2) use can be made of arithmetic units of parallel digital differential analyzers to perform in a digital form the operations similar to those performed by the computing elements of analog computers;

(3) multipurpose or special-purpose analog computers can be included as part of a computing system.

Any of these variants realized either separately or in combination with others has its own set of tradeoffs. But the analog computer is still more advantageous in terms of computing speed, particularly if there are complex functional relationships in the right-hand sides of the discussed equations. This advantage is enhanced by the flexibility and high logical possibilities of hybrid computing systems used in the analysis of large dynamic systems, including power systems.

Logically, there is a trend to combine the analog and digital computers in one computing system which allows one to make most of the capabilities of different types of computers.

Types of hybrid computers. According to the different combinations of computing elements that go to make a hybrid computer, hybrid computers can be broadly classed into the following types:

(1) analog-oriented hybrid computers characterized by a large analog section and a small digital section used primarily to control operation of the analog section;

(2) digital-oriented hybrid computers characterized by a large digital section and a small analog section which finds limited application, e.g. for simulating very fast processes;

(3) balanced hybrid computers in which the computing power of the analog and digital sections is approximately equal and they take equal part in the computing process.

These hybrid computers can be based either on multipurpose equipment or on the equipment specially intended for operation within the hybrid computer. In any case, the analog and digital sections are supplemented with converters for converting data from one form of representation to another (i.e. analog-to-digital and digital-to-analog converters abbreviated ADC and DAC) and also other requisite devices which are discussed later in more detail. Attempts to use sequential and repetitive structures in analog computers were dictated by the economic considerations inasmuch as analog simulation of complex power systems involves the use of large amounts of hardware (hundreds of computing elements, sophisticated function generators and multipliers). The concept of repetitive use computing elements is illustrated in Fig. 6.3. As seen from the figure, a computing element which is essentially a function generator is connected through a commutator to the contacts at which appear signals x_1, x_2, . . ., x_m, which may represent, for example, the angles between the rotors of synchronous generators in their relative motion. The data are stored in the analog storage devices. A commutator is also provided at the output of the element, and it moves in step and in phase with the main commutator. If the rate of motion is fast enough, one and the same element may convert all the signals

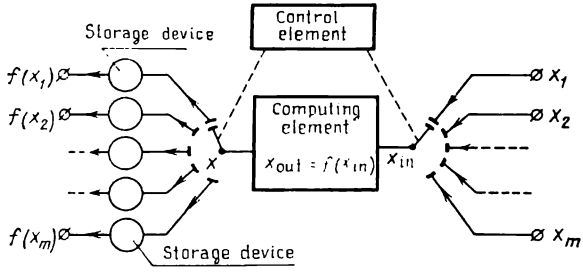


Fig. 6.3

applied to it, acting as a substitute for m elements which would be otherwise required in the absence of the commutator.

For normal functioning of the obtained sequential structure, the following basic requirements should be fulfilled:

(1) the analog memory should hold initial data in the form of settings of the elements of the model and control devices, initial conditions, etc. The interim results should be also stored. If it were not so, the signal $f(x)$ would disappear from the element connected to the brush as it moves away from the respective position and the circuit would become inoperative. The circuits for storage of analog signals are rather complex and cannot be used in quantity. This imposes a limitation on the repetitive operation;

(2) the switching rate of the circuit in a device intended for repetitive use of computing elements should correspond to the provisions of one of the pulse theorems (the Kotelnikov-Shannon theorem) which states that in order to avoid the loss of information, the commutator brush should be connected in a particular case to each circuit at least twice for the period τ_{mi} of the highest-harmonic frequency f_{mi} of the signal in this circuit. Thus, with the commutator scanning periodically the circuits connected to it, the scanning period T_i, which is otherwise called the information update cycle, must be defined as

$$T_i = 2K/f_m \tag{6.1}$$

where T_i is the highest-harmonic frequency of the signals in all the circuits connected to the commutator; $K = 0.1\text{-}0.2$ depends on the precision required.

If condition (6.1) is not observed for some reason or other, the circuit can be placed in the "Hold" condition when the computation is stopped and the values of all variables remain unchanged (stored by the capacitors of the integrators). This condition can be introduced in all analog computers to register the values of variables in time by means of conventional indicating meters, although a certain period of time is required to effect a transfer to this condition.

Due to the above considerations, the computing elements are not practical to use for repetitive operation in the analog subsystems of hybrid computing systems and the above-mentioned conditions chiefly apply to the so-called multichannel analog-to-digital converters.

6.2. Building Blocks of Analog, Hybrid Computers and Hybrid Computing Systems

As applied to the power industry, the solution of problems on analog computers and hybrid computing systems cannot be evaluated in isolation either from the technical capabilities or the nature of the problem to be solved.

So, when investigating the behaviour of a power system at the limits of stability, it should be taken into account that the simulating analog computer also operates with marginal stability and the obtained result may be somewhat distorted due to the effect of spurious parameters in this system, and these unwanted parameters should be duly considered and suppressed.

This constitutes one of the basic disadvantages of the analog computers and hybrid computing systems. Nevertheless, all process control systems and corresponding automated dispatch control systems are in essence large hybrid computing systems where the continuous information processing facilities interact with discrete computing devices. This also holds true for the automatic control equipment of the power systems when it interacts with the digital computers within an automatic dispatch control system. Such relationship also exists in the telemetering and teleindication systems and CRT display units which utilize the elements first developed specifically for the analog and hybrid computing systems. The computing machinery and systems of this type can be regarded as the models of real systems.

Operational amplifiers. An operational amplifier is a circuit comprising the operational amplifier proper and a negative feedback loop, which consists of input elements (placed between the inputs of the entire circuit and the amplifier proper) and feedback elements (placed between the output of the entire circuit and the input of the amplifier proper). A block diagram of an operational amplifier is shown in Fig. 6.4, where multiterminal network I is an input element and multiterminal network II is a feedback element. The output currents of these multiterminal networks are summed at the input of the operational amplifier at a junction Σ which is known as the summing junction.

If we assume that $I_\Sigma = 0$ and $e^\Sigma = 0$ since the open-loop gain of the amplifier K_a tends to infinity ($K_a \to \infty$), then we shall obtain a known equation

$$I_1 (V_0, V_1, V_2, \ldots, V_m, p) = I_2 (V_0, V_{out}, p) \qquad (6.2)$$

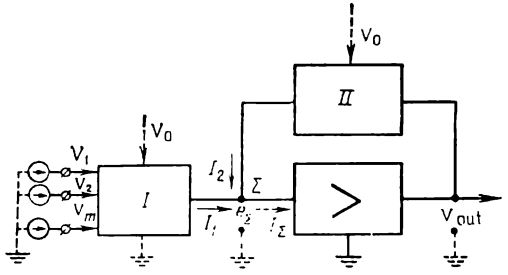


Fig. 6.4

from which we can compute the value of output voltage V_{out} for any other voltages in the network and for any admittance conditions existing in the multiterminal networks. Thus, for instance, with

$$I_1(V_0, V_1, \ldots, V_m, p) = \sum_{i=1}^{m} \frac{V_i}{R_i} \tag{6.3}$$

$$I_2(V_0, V_{out}, p) = V_{out}/R_{fb} \tag{6.4}$$

where R_b is the resultant feedback resistance, the output voltage will be

$$V_{out} = -R_{fb} \sum_{i=1}^{m} \frac{V_i}{R_i}$$

so that the amplifier performs the function of a summer.

With expression (6.3) remaining unchanged, let us substitute equation (6.4) by

$$I_2(V_0, V_{out}, p) = -CpV_{out} \tag{6.5}$$

then

$$V_{out} = -\frac{1}{Cp} \sum_{i=1}^{m} \frac{V_i}{R_i} \tag{6.6}$$

i.e. the amplifier becomes a summing integrator.

Proceeding in a similar manner, one can obtain the operators reproduced by the network when the admittance in any one of the multiterminal networks exhibits nonlinearity, and it can also vary with varying reference voltage E_0, etc.

To analyze the operation of the amplifier, consider a typical case when it is used to represent a linear element.

Assume that $I_\Sigma = 0$ and the amplifier input is connected only to one circuit with operator impedance $Z_{in}(p)$, with the impedance of

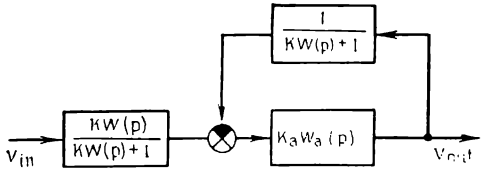


Fig. 6.5

its feedback element being $Z_{fb}(p)$. Then with $K_a = \infty$ the value $e_\Sigma = 0$ and the transfer coefficient of the network derived from (6.2) will take the form:

$$KW = V_{out}(p)/V_{in}(p) = Z_{fb}(p)/Z_{in}(p) \tag{6.7}$$

Let the amplifier gain be a finite value equal to K_aW_a and then, using the superposition principle, the network can be replaced by the one shown in Fig. 6.5. Now, we can easily obtain the real value of the network transfer coefficient as follows:

$$K'W'(p) = KW(p)\frac{K_aW_a(p)}{K_aW_a(p) + KW(p) + 1} + \frac{1}{K_aW_a(p) + KW(p) + 1} \tag{6.8}$$

To begin with, consider a summing amplifier which is frequently called a scaler when it has one input circuit. In this case $KW(p) = K \ll K_a$, $1 \ll K_a$, so that neglecting the last term in expression (6.8), under steady-state conditions, we get

$$K' = K\frac{1}{1 + (K+1)/K_a} \tag{6.9}$$

giving rise to the so-called static frequency slope error which under the specified conditions can be approximately defined as

$$\Delta = (K' - K)/K' \approx (K + 1)/K_a \tag{6.10}$$

Expression (6.10) is of major importance in the theory and practical application of the operational amplifiers due to the fact that in ordinary high-gain electronic amplifiers it is extremely difficult (at any K_a) to stabilize this value which is dependent on many factors (such as temperature, supply voltage, etc.). Expression (6.10) shows that this does not apply to the network illustrated in Fig. 6.5 because, with the overall gain of the network established at $K = 100$, the variation of the open-loop gain of the operational amplifier from 1 million to 100 000 would result in the variation of the static frequency slope from 0.001% to 0.01%, which is an acceptable figure under normal conditions.

So, the first major property of the operational amplifier lies in the fact that the amount of gain of an operational amplifier is of little importance provided its open-loop gain is sufficiently high.

The property outlined above is common both to the first-generation analog computers employing electron tubes and to the second-generation analog computers employing semiconductors but has become of critical importance with the advent of third generation computers. Indeed, modern microelectronic techniques make it possible to pack five to eight stages of a d.c. converter with all associated components on an area several millimeters square (with the exception of frequency-compensating capacitors), with the parameter spread to an order of magnitude. If the operational amplifiers lacked this property, they would be difficult to realize using the integrated-circuit techniques.

The second major property of the operational amplifier consists in that a large amount of negative feedback can minimize the output drift and other changes occurring within the operational amplifier. It is known that with a constant signal applied to the input of a d.c. amplifier stage of any type, the output signal experiences gradual changes caused by the variations in the ambient temperature, supply voltage and the time factor.

Such variations of the output signals for constant input signals are termed *amplifier drift*. The cause of amplifier drift cannot be eliminated as it is associated with molecular phenomena. In a.c. amplifiers, these slow variations are coupled out by the various blocking elements (capacitors, transformers) and do not affect the output characteristics. In the so-called conductively-coupled d.c. amplifiers, the output can be directly affected by drift unless special precautions are taken.

Quantitatively, the effect of drift is estimated using its equivalent (or reduced) value which is determined as a voltage applied to the summing junction Σ of the amplifier (see Fig. 6.5). Then for the scaling amplifier we have

$$\Delta u_{dr} = e_{dr} (K + 1) \tag{6.11}$$

and, accordingly, the effect of the drift on the resultant error is the more pronounced the higher is the gain K. From this it follows that if there are several inputs, the effective value of the gain, K_{eff}, is determined considering that all input resistances are connected in parallel, i.e.:

$$K_{eff} = R_{fb} \sum_{i=1}^{m} \frac{1}{R_i} \tag{6.12}$$

As concerns semiconductor and integrated-circuit amplifiers, one more component should be added to the drift voltage to account for

the variations in the input current, I_Σ. Assume that the random, or temperature, components of the current variations have a value i_{dr}. Then, in order to cancel it in a summer or scaler, a current of the same value should flow through the output resistor, and this will be practicable when the output voltage is

$$\Delta u_{dr.c} = i_{dr} R_{fb} \tag{6.13}$$

Thus, knowing the value i_{dr} which is dependent on the temperature, it will be a simple matter to predict the possible drift of the output quantity*.

Similarly to the drift, a large amount of negative feedback eliminates the influence of internal resistance on the performance of the operational amplifier by converting it into a voltage source. The resistance connected between the output of the operational amplifier and the point of connection of the feedback element will be minimized $(K_a + 1)/K$ times when the amplifier operates as a summer in the linear zone. This capability is put to effective use in specialized applications.

The third major property consists in the ability to stimulate dynamic response of the feedback network and suppress the spurious dynamic response of the operational amplifier itself. It will be readily apparent that as a voltage surge ΔU occurs at the input of the integrating amplifier, its output voltage will vary as it would have varied in a passive integrating RC-network with similar feedback loop parameters in the event of a voltage surge equal to $\Delta V K_a$.

However, the dynamic range of the amplifier output voltage (its scale) is usually much less than $\Delta V K_a$, so that use is made of a nearly linear initial portion of the exponential curve, which means that the actual integrating operator differs but little from the ideal one.

At the same time, a reduction in the gain caused by the increasing frequency, a feature characteristic of all practical amplifiers including operational, will result in a static frequency slope error in the case of a summer [refer to (6.10)] and an additional phase shift that can be determined from the value $W(j\omega)$.

The properties outlined above remain effective until the amplifier is beyond its scale, or its stability is impaired. These conditions are very important.

A scale of an operational amplifier defines its output voltage range V_m; when the amplifier goes off scale, the proportionality of this voltage to the amplifier input signal is not ensured. For convenience, the final value of the voltage scale is made rounded (100, 10 V, etc.) indicating the rated load of the amplifier (usually resistive, in ohms).

---

* The amplifier drift is intrinsically different from the offset which can be corrected by means of a zero-setting circuit.

If the amplifier load rating is exceeded (when the load resistance is too low), the required proportionality may be disturbed at voltages lying within the output voltage range. If the loading is below the rated value, the proportionality margin may be somewhat higher (owing to some intrinsic capabilities). With slow (static) variations of the output voltage, the proportionality margin is determined by the characteristics of the output stage, manifesting itself as a sharp bend in the amplifier characteristic which becomes almost horizontal.

At higher frequencies, proportionality may be at first impaired in the intermediate stages, resulting in the distortion of the output voltage curve. Therefore, one of the major characteristics of the operational amplifier is the maximum frequency F_m of an undistorted output sine signal with an amplitude V_m or the maximum rate of output voltage buildup dV_{out}/dt approximately defined as $2V_mF_m$.

Stability of an operational amplifier defines the stability of the loop (Fig. 6.5) which is determined by the inherent characteristics of the amplifier [its transfer coefficient $K_aW_a(p)$] and by the parameters of the feedback loop dependent on the operation being executed, i.e. $1/[KW(p) + 1]$.

A structural analysis will show that, other conditions being equal, the stability margin is the highest with the integrator and the lowest with the differentiator. As for scalers and summers, their stability margin is determined by the gain of the loop in question and is the smaller, the smaller is the value of K. It is also dependent on the output capacitive load and other factors.

The design of present-day operational amplifiers provides for loop stability at all K, including $K < 1$, and with the amplifier input and output capacitances being of the order of hundreds and even thousands of picofarads (as referred to the distributed wiring capacitance of the analog computer). Depending on the accuracy class and circuit design, the amplifier characteristics may range within the limits specified in Table 6.1.

Table 6.1

Design	Characteristics					
	gain	voltage range, V	output current, mA, min	voltage drift, μV/deg	current drift, A/deg	unit gain frequency
Integrated-circuit	10^4-10^{-8}	10-12	5-20	20-30	$5\cdot10^{-8}$-10^{-11}	0.5-50 MHz
Hybrid (integrated circuits with discrete components)	10^5-10^{-8}	10-100	10-500	0.1-20	$5\cdot10^{-9}$-10^{-13}	1-1000 MHz

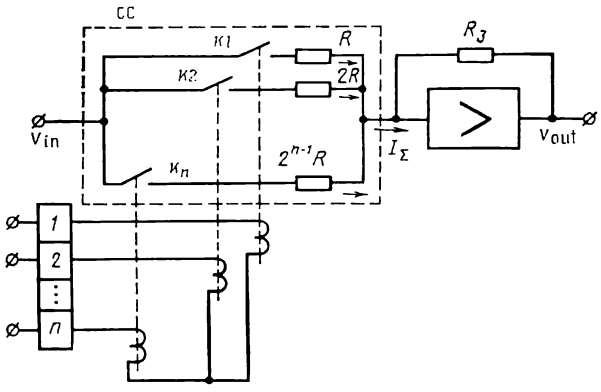


Fig. 6.6

At a low output voltage (provided there are no saturated stages), the amplifiers can pass signals varying in frequency from zero to several megahertz and even tens of megahertz. Under these conditions, they are capable of reproducing the linear operators; with high precision, serving as basic elements for the reproduction of nonlinear operators.

Operational amplifiers with gated resistance networks. The ability of operational amplifiers to accurately sum currents is frequently used as a means for conversion from the digital to the analog form of information representation as well as for the combination of the two. For this purpose, a special device, called a *gated resistance network*, is connected to the amplifier input as shown in Fig. 6.6. It represents an assemblage of relays and static switches of different types and resistors selected according to the law frequently referred to as the law of R—$2R$. According to this law, each succeeding resistance is assumed to be twice the preceding resistance. It can be easily shown that in keeping with this law the total input current is

$$I_\Sigma = \frac{N}{2^n - 1} \cdot \frac{V_{in}}{R} \tag{6.14}$$

where n is the number of resistors; N is a certain number expressed by n bits and fed into the device as shown in the figure, i.e. with the most significant digit coming first.

Resistor R_{fb} is placed in the feedback loop of the amplifier.

If the precision of assorted resistors that make up the current converter (CC) is sufficiently high, then the circuit under consideration will make it possible to:

(1) use relays as switches, with the control signals fed from the keyboard, punched tape, etc., and to represent the voltage V_{in} as

an input signal to the operational amplifier. The circuit may be used for setting the transfer coefficients of the operational amplifiers specified when the problem is set up in a digital form;

(2) make the static switches operate when the input voltage remains unchanged in magnitude and sign. To do so, one can feed the control circuits of the switches with a certain binary number in order to obtain its analog on the established scale (determined by V_{in} and R), i.e. to perform digital-to-analog conversion (a complete digital-to-analog converter also incorporates a storage device of its own for storing the numerical code of the number);

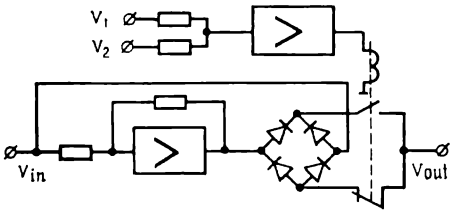


Fig. 6.7

(3) create static switches which can operate regardless of the changes in the magnitude and sign of the input voltage. This leads to the creation of a circuit called "multiplying DAC" which performs the specified functions and provides for multiplication of a continuous quantity by a discrete number.

All these capabilities are realized when the computing and automatic control devices employ operational amplifiers.

Operational amplifier as a comparator (null detector). Operational amplifiers which satisfy the minimum drift and high speed requirements are ideal comparators for collating the values of two currents or voltages. Such amplifiers can operate either without the feedback element or with a feedback element in the form of a limiter. In this case, a change in the sign of the difference of the signals applied (occurring when the amount of drift is too high) will cause a step-like change in the output signal whose value will be equal to V_m or to the limiting threshold, and the sign will be the opposite of the difference sign.

The amplifier comparator should have a relay or a switch at its output to introduce the desired changes in the problem setup (conditional transfers). One of the practical setups to effect sign inversion (step function) is shown in Fig. 6.7, where the output voltage is defined as

$$V_{out} = \text{sign}\,(V_1 - V_2)\,|V_{in}| \tag{6.15}$$

With the appearance of integrated-circuit amplifiers, the operational amplifiers came to be used as comparators in ever increasing numbers and the construction of many relays became greatly simplified.

Operational amplifier as a generator of time functions and CRT display symbols. Fig. 6.8 shows three versions of an amplifier:

(a) a generator producing a linearly rising voltage varying in accordance with the initial-condition voltage (IC) and the integrator transfer coefficient. This voltage may be applied either to the comparator, thus forming a time relay (counter), or to a general-purpose function generator (FG), making it possible to obtain an arbitrary time function within the operating range of the integrator;

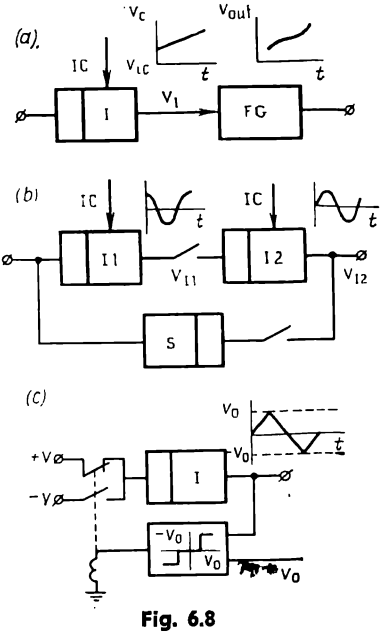


Fig. 6.8

(b) a harmonic oscillator, whose output conforms to the solution of an ordinary linear differential equation with constant coefficients. If voltages V_{I1} and V_{I2} are applied to the two mutually perpendicular plates of a cathode-ray tube, an ellipse or a circle will appear on the CRT screen. If we disconnect integrator $I1$ and let integrator $I2$ operate as a sawtooth voltage generator, then we can obtain on the CRT straight lines tilted at different angles;

(c) a triangular wave generator which produces oscillations as a result of interaction between the integrator and comparator and a relay that switches the voltage to be integrated. It is assumed that the comparator has a symmetrical characteristic and changes the position of relay contacts each time the integrator output voltage reaches $|V_0|$. Clearly, the output voltage frequency f is defined through V, V_0 and the transfer coefficient of the integrator $1/T$ as

$$f = (1/2T)\ (V/V_0) \qquad (6.16)$$

Such generators are utilized in special-purpose computers intended for analyzing electromechanical transient processes in power systems.

Operational amplifier as a storage device. In such applications, the function of the operation amplifier is based on its ability to hold a capacitor charge constant after its input circuit is opened (Fig. 6.9). When switch S is closed, the circuit exhibits aperiodic behaviour, following with some delay the input voltage V_{in}. If switch S is open, the capacitor charge and the amplifier output voltage will remain constant for a long time. If the time constant R_2C_2 of such an aperiodic element is large, such circuits are called track and store

amplifiers and are referred to as measuring and storage circuits if the time constant is small.

The storage devices of this type are widely used in hybrid computing systems to effect transfer from the parallel to the sequential structures and vice versa and also for solution of some problems involving emergency control schemes of the power systems. Besides, the ability to store information which is typical of all operational amplifiers may be employed to reproduce the functions of pure (transportation) lag and to realize the iterative procedures. Operational amplifiers used in such applications are termed sample-hold amplifiers. The operational amplifiers form the basis of the majority of devices used to perform nonlinear operations in the analog computers.

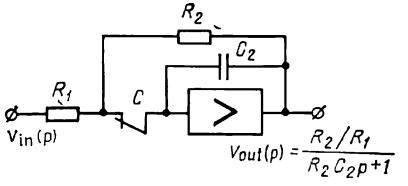


Fig. 6.9

Function generators and multipliers. As a rule, nonlinear functions are represented in analog computers using direct readout. The readers perform the same functions as the ROMs and PROMs but are based on different principles.

As applied to analog computers, the electromechanical devices intended to perform nonlinear operations are usually made as a combination of two devices, one of which converts an input signal X into an angle of turn of a certain mechanical shaft θ and the other, multiplies by an angle θ another signal Y, performing upon it a functional conversion. In this way, an operation of the form

$$Z = f(X)\, Y$$

is executed so that at $f(X) = X$ the device in question operates as a multiplier and, at $Y = 1 = \text{const}$, as a function generator.

Physically, such devices are realized by means of an electromechanical servo system comprising a motor, an amplifier, an angular position transducer, linear and nonlinear potentiometers. A nonlinear potentiometer may be defined as a potentiometer made to represent a specific function of the input signal with respect to angle θ (Fig. 6.10). These potentiometers are realized either on the basis of linear potentiometers (Fig. 6.10*a*) or in the form of switches using the arrangement shown in Fig. 6.10*b* (in this case, the required relationship is represented by the settings of resistors $r_1 - r_m$). In addition, use is made of special photoelectric servo systems (automatic curve followers) in which a graph of the function $f(X)$ drawn on ordinary paper is attached to a revolving drum and is traced by a mechanically positioned reading head.

Both types of electromechanical function generators are developed and manufactured both for the multipurpose analog computers

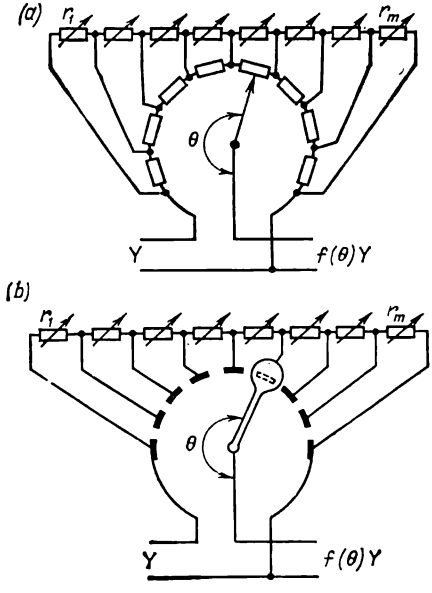


Fig. 6.10

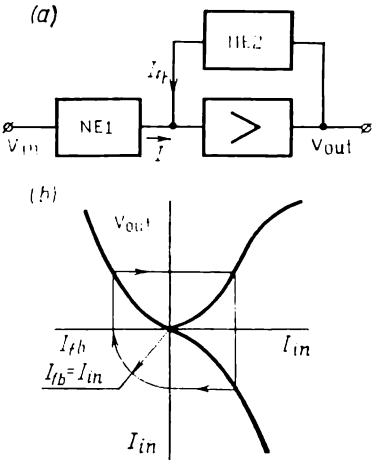


Fig. 6.11

and special-purpose equipment intended for load frequency control and economic dispatch in power systems. An advantage of these function generators is the possibility of arranging several nonlinear potentiometers or drums with graphs on the shaft of one servo system and obtaining a number of functions such as the output of the power stations for one and the same value of relative increment in the power system. However, the performance characteristics of these devices are not very promising and they are being gradually ousted by those with higher reliability. General-purpose analog computers should have an accuracy better than 0.5-1.5% which requires that the rate of change of X be limited to 300-500 deg/s with respect to $d\theta/dt$.

For this reason, such devices are used but seldom, giving way to the electronic function generators and multipliers which rely for their operation on nonlinear resistors placed in the feedback networks of operational amplifiers. This principle is outlined in the diagram shown in Fig. 6.11*a*. By connecting elements *NE1* and *NE2* with nonlinear voltage-current characteristics of a certain kind (which are frequently called current characteristics) to the input and in the feedback loop of the amplifier, it is possible to obtain the output voltage that is a function of the input voltage (Fig. 6.11*b*).

Besides, use may be made of one nonlinear element (the other being linear). This approach is not always practical as it is more difficult

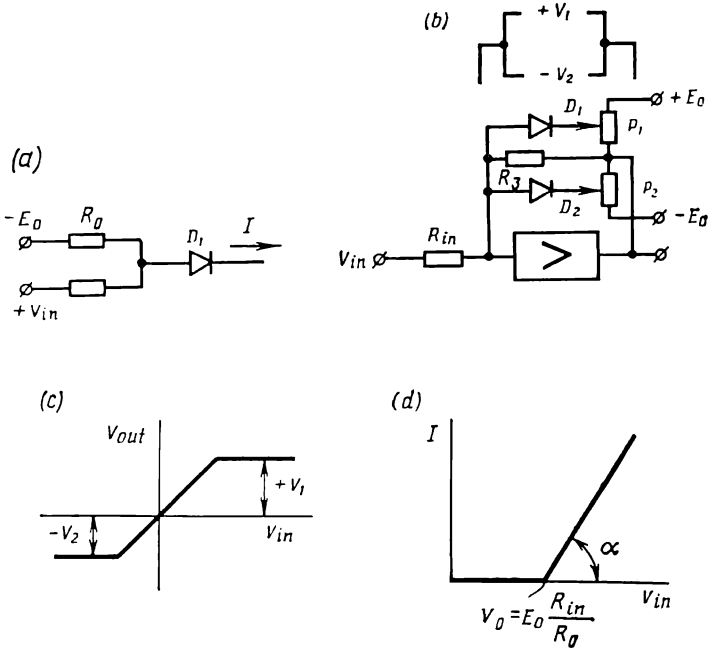


Fig. 6.12

to obtain an upward voltage-current curve than a downward. Multiplication is performed by the square-law function generators by computing the difference between the squares of the half-sum and half-difference of the factors.

To sum up, the primary feature to be considered in the function generators and multipliers of analog computers is the provision of highly accurate and stable artificial nonlinear resistances. In addition, the general-purpose function generators should provide the means for fast and flexible variations in, say, current characteristic.

Such characteristics are usually obtained with the use of diode elements (Fig. 6.12) controlled by the stabilized reference voltage $+E_0$ or $-E_0$, thereby providing for piecewise-linear approximation of the characteristics concerned (as required, use may be made of an additional input signal $-V_{in}$ produced by an inverter). The simplest diode element is a two-terminal diode (Fig. 6.12*a*), typically used to simulate nonlinear relationships commonly encountered in dynamic systems, such as dead zone, backlash, etc.

Figure 6.12*b* shows a nonlinear characteristic implemented by the circuit shown in Fig. 6.12*c* and called a limiter (the feedback element is denoted by the symbol shown at top right above Fig. 6.12*c*).

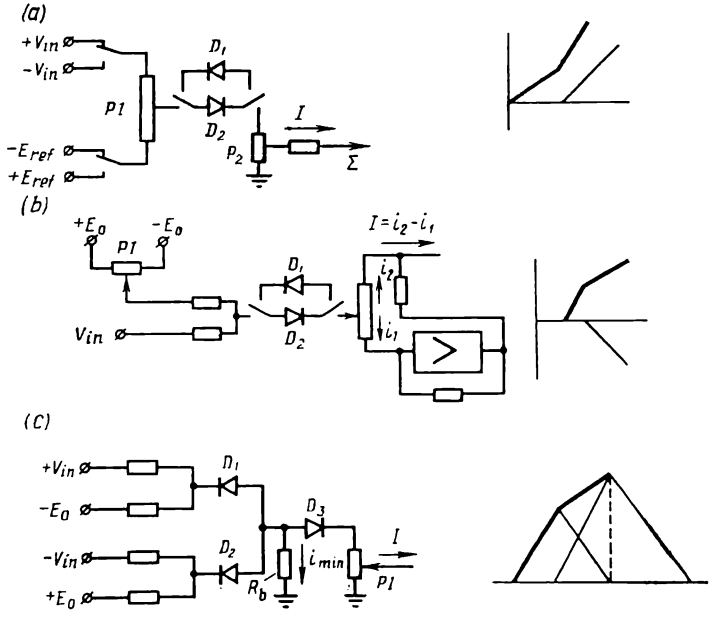


Fig. 6.13

The circuit operates on the principle that the current characteristic of a two-terminal diode (Fig. 6.12*d*) is expressed as

$$I = 0 \text{ at } V_{in}/R_{in} \leqslant E_0/R_0$$
$$I = V_{in}/R_{in} - E_0/R_0 \text{ at } V_{in}/R_{in} > E_0/R_0 \qquad (6.17)$$

The characteristic consists of two line segments emanating from the breakpoint V_0 of the diode element. One of the line segments lies along the X-axis and the other slopes away from it at an arbitrary angle α. Linear characteristics are also exhibited by other elements (Fig. 6.13) used in the function generators of various types. Typically, each such generator consists of m similar diode elements ($m = 12$ to 15 or more), supplemented with a linear element ($I_l = kV_{in}$) and an element to form the direct component of the function being generated ($I_0 = CV_c = \text{const}$).

The output currents of the elements are summed by an amplifier with feedback resistor R_{fb}, permitting piecewise-linear approximation of the given function with the nodes of approximation at the breakpoints of diode elements V_{0i}:

$$V_{out} = R_{fb}\left(\sum_{i=1}^{m} I_i + I_l + I_0\right) = \sum_{i=1}^{m} f(V_{in}, V_{0i}\alpha_i) + kV_{in} + V_c \qquad (6.18)$$

As seen from the inspection of Fig. 6.13, the basic difference between the elements lies in the method of generating the required function with the required number of switchings. So, the elements of older type used in the analog computers (Fig. 6.13*a*) required up to two switchings (to select the half-plane and the quadrant). In newer elements (Fig. 6.13*b*), the output current is formed by adding two currents (i_1 and i_2) of different polarity so that only one switching can take place.

A distinguishing feature of all function generators used in multipurpose analog computers is that a definite sequence of steps must be closely followed when selecting the desired function, or else, the entire function will have to be readjusted in order to change the ordinate at any intermediate approximation point. A new type of diode elements (Fig. 6.13*c*) has evolved as a result of development of special-purpose computers for application in power industry. This arrangement involves interaction of two two-terminal diode elements with intersecting current characteristics shown in broken lines in the diagram.

In analog computer practice, such circuits are used to select the smaller value. The circuit action consists in that a voltage drop is developed across ballast resistor R_b due to the effect of the least of two currents (i_1 or i_2) and then switched by diode *D3*. As a result, the two intersecting line segments of the current characteristics of the two-terminal elements will form a triangle. Now, to change each ordinate of the function being approximated, it will suffice to change the setting of only one potentiometer.

The functions performed by diodes *D1*, *D2* and *D3* in this circuit can be compared to the functions of gates in discrete logic circuits. Here, the logical **OR** function corresponds to the selection of the smaller value and the logical **AND** function, to the switching operation. By connecting potentiometer *P1* to the voltage source e instead of ground, one can obtain the function of three variables defined in accordance with the laws of continuous logic as

$$\lambda (U_{in}) = [X_1 (V_{in}) \wedge X_2 (V_{in})] \vee X_3 (e) \qquad (6.19)$$

The adjustment of function generators is one of the most laborious tasks connected with the use of analog computers. To simplify this procedure, use is made of function generators preadjusted to generate a specific function. The so-called sine-cosine elements are also of great importance.

Switches. These comprise the elements intended for signal switching and sufficiently distortion-free to pass currents of different polarity varying within wide limits. In the closed (conducting) state, the resistance of the switch tends to zero and in the open (nonconducting) state, it considerably exceeds the working resistance measured in megohms. The switches should meet the requirements of compactness, reliability in operation and high switching speed.

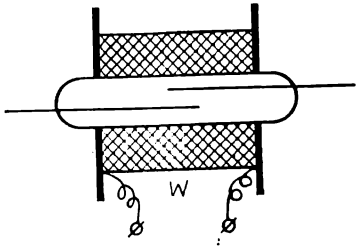


Fig. 6.14

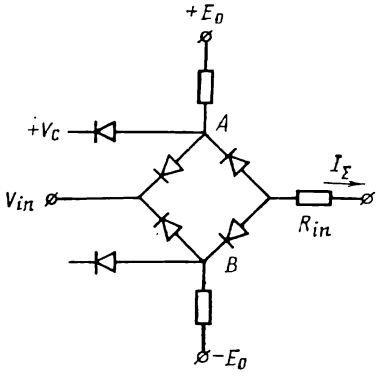


Fig. 6.15

Such switches are much more difficult to realize than the switches for discrete signals.

Polarized relays were the first switching devices used in analog computers. In the mid-1960s, these relays were ousted by sealed-contact reed relays (with reed contacts). These contacts (Fig. 6.14) are in the form of two strips, one of which is made from a magnetic material while the other is of a nonmagnetic material. The strips are hermetically sealed in a glass tube filled with inert gas. In the presence of magnetic field (set up by coil W placed around the relay), the contacts close and open when the field is removed.

Owing to their small size (the diameter of a 30-50 mm long tube is 4-6 mm) and insignificant sluggishness of the contacts, the sealed-contact reed relays satisfy most of the requirements stated above and find wide application in second-generation analog computers. With the advent of the third generation of computers, however, the switching speed of reed relays (the operate time of about 1 μs with 0.1 to 0.2 μs taken by contact chatter) has become inadequate, making them a poor match for the static diode and transistor switches whose speed is close to that of the gates used in digital computers.

The most popular is a six-diode switch (Fig. 6.15) controlled by signals of different polarity with respect to ground ($+V_c$ and $-V_c$), with the absolute value of these signals not below the value of the input voltage V_{in} to be switched. Let both control voltages $+V_c$ and $-V_c$ be equal to zero. Then there will be no voltage at the junction A or B relative to ground and the current passing through resistor R_{in} to the summing junction of the amplifier following the switch will be also equal to zero. With positive voltage V_{in} applied to the circuit, voltage $V_A = V_{in}$ will appear across the junction A and the same voltage will appear across the junction B when the

voltage V_{in} is negative. The six-diode switch may be placed after resistor R_{in} to switch the current directly, but in this case the effect of unbalance in the bridge arms on the operation of the circuit will be all the more pronounced.

The disadvantage of the six-diode switch with its complex multielement circuit arrangement is offset by the use of transistor switches, and particularly those employing field-effect transistors, where the voltage across one of the electrodes (gate) sets up an electric field that controls conduction through the channel between the other two electrodes (drain and source). When the switch is turned off (pinched off), its channel resistance (which does not exceed several hundred ohms when the switch is turned on) is extremely high and is practically linear to be accounted for in the value of R_{in}. In addition, there exist various integrated-circuit analog (linear) switches which provide for high-speed switching of analog signals.

Information representation converters. Such converters are needed to serve as an interface between continuously and discretely operating devices and find application in hybrid computers and pulse-code telecontrol equipment. They comprise digital-to-analog converters (DAC) whose speed is determined by the speed of switching devices (there must be several hundred thousand conversions per second) and analog-to-digital converters (ADC).

The use of such converters results not only in the transition from one form of information representation to the other but often in the transition from the sequential to the parallel organization of the computing process. In such applications, a digital channel can be used for serial transmission of the values of various parameters characterizing the transfer coefficients of the various computing elements of the analog computers, etc. This necessitates code switching and code storage for the digital or analog equipment. In the former case, the digital-to-analog converter is provided with flip-flop registers and in the latter, use is made of various types of analog storage devices.

Early analog-to-digital converters were based on the principle of linear conversion and had a typical arrangement shown in Fig. 6.16*a*, where a sawtooth voltage (V_1) generator was activated at the same time when a train of stable-frequency pulses was furnished to the counter (Ct). When the voltage V_1 coincided with the input voltage, the comparator terminated the pulse count by manipulating switch *S1* and made switch *S2* transfer the contents of the counter to the converter output as a digital equivalent x_d of the input analog quantity V_{in} (x_a).

The creation of precision current converters made possible the extensive use of digital servo systems (Fig. 6.16*b*). Referring to the diagram, reversible counter Ct_r either increments or decrements depending on the point of application of a train of pulses and con-

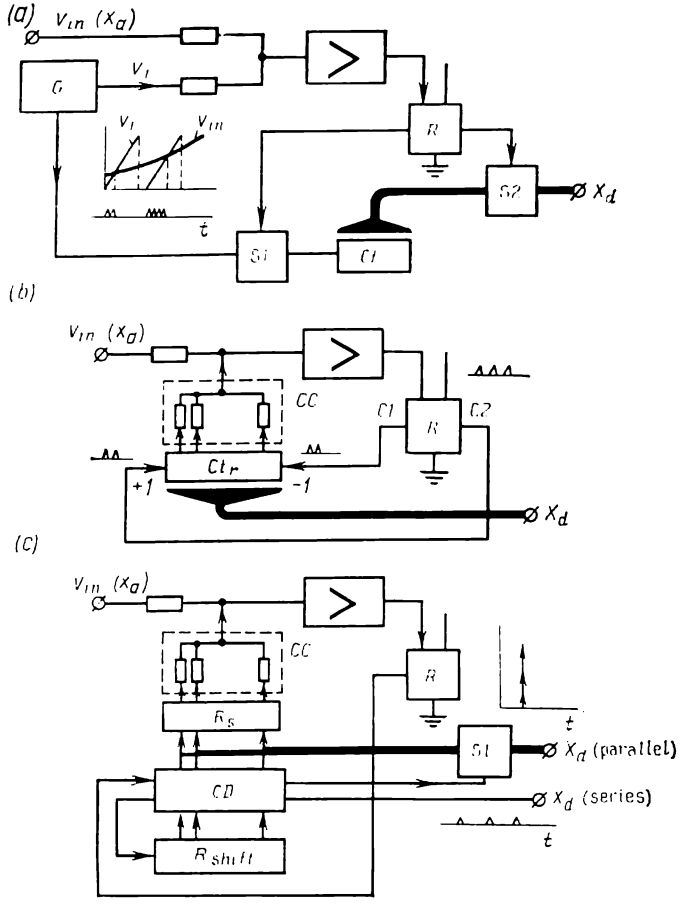


Fig. 6.16

tacts *C1* and *C2* of a two-step relay *R* (gate) open and close depending on the sign of signal difference.

This arrangement is suitable for single-channel conversion when one value is constantly fed into the analog-to-digital converter and the counter rapidly changes its contents in response to the variations in this value. By contrast, in the multichannel analog-to-digital converters where different and sharply contrasting values are fed into the converter, the necessity for quick response to the variations in these values leads to a reduction in the operating speed. For example, if we have a ten-digit counter and the value of each complemen-

ting one constitutes 0.001 of the quantity to be converted, then the counter must count about 600 pulses when the value of the input signal changes from 0.2 to 0.8.

A disadvantage of this circuit is the large processing time which is overcome in the circuit employing the principle of successive approximation (feedback subtraction). The circuit is presented in Fig. 6.16*c* and is widely used in computing, automatic control and telecontrol equipment. This arrangement is characterized by the use of a shift register (R_{shift}) instead of the pulse counter and an additional storage register (R_s) connected with the shift register through a control circuit (CC).

As before, pulses are fed to the shift register through the comparator relay but they are not counted, causing the one in the register to shift by one digit position from the more significant digits towards the less significant digits (down shift). Through gate G, this one is transferred to the storage register in the following order. A one moved into the storage register is erased from it if it causes the comparator to change state. If not, the one is held in the register. The sequence of steps involved in conversion can be traced using a concrete example.

Let us convert a number of the form

$$\frac{512}{1\,024}+\frac{128}{1\,024}+\frac{32}{1\,024}+\frac{16}{1\,024}+\frac{4}{1\,024}+\frac{1}{1\,024}=0.6769=\frac{693}{1\,024}$$

In binary notation, the number will look like 10101010101 in agreed interpretation. The conversion will start by moving a one in the most significant digit position of the shift register. When transferred to the storage register, it will not cause the comparator to change state so that the one will occupy the most significant digit position of the storage register and will move to the next digit position in the shift register. Since $\frac{512}{1\,024}+\frac{256}{1\,024}$ is greater than the number $\frac{693}{1\,024}$ to be converted, the comparator will change state at once and, accordingly, the one in the second digit position of the storage register will be replaced by a zero and the one in the shift register will be shifted to the next digit position. As a result, a one will appear in the third digit position of the storage register and so on until all the bits have been sampled (weighted). Apparently, the number of shifts and transfers (which equals 20 in an 11-bit register) will be much smaller than the number of pulses which would have to be counted by the counter to counterbalance the specified number when using the digital servo system.

The output binary code is formed by the storage register in a serial manner, i.e. bit by bit, and can be immediately transferred to a communication channel, constituting a transition from the parallel to the sequential code in the most convenient form (without any

corrections). Therefore, practically all the converters currently in use have this circuit configuration but, if need be, can be converted to the circuit shown in Fig. 6.16*b* by changing the mode of operation of the registers. At the clock frequency of hundreds of kilohertz and 11-12 bits, these converters permit several thousand conversions to be made per second to an accuracy of four decimal places, making them suitable for connection of a number of input channels through a multiplexor. The number of the channels is determined by using expression (6.1).

6.3. Application of Multipurpose Analog and Hybrid Computers in Power Industry

Multipurpose analog computers are constructed from d.c. operational amplifiers and hybrid computers consist of an analog and digital sections. The basic features of these machines are described herein in relation to their application in the power industry and problems associated with dispatch control of the power systems.

Parallel execution of computations underlying the operation of analog computers makes their structure more flexible as compared to digital computers. Indeed, each computing element of the analog computer is a self-contained entity having input/output relations with other elements. Attempts to organize these relations in the form of a connection matrix (Fig. 6.17*a*) have met with no success as a result of incomplete filling of the matrices. As an alternative, preference was given to the analog computer setups like the one shown in Fig. 6.17*b*. The connections between the computing elements are by means of patch cords plugged into special patch panels.

Practical elements of analog computers. The functional independence of the computing elements of analog computers found its physical realization in their construction. Apart from rack-type construction of the analog computers where all computing elements are installed in a common rack or cabinet, the computing elements are unitized to form self-contained assemblies. Besides, groups of elements can be combined into separate devices that make up analog computing systems.

The combinations of computing elements in multipurpose analog computers are not subject to strict limitations. Up to now, no effective quantitative relationship has been found between the various computing elements (both linear and nonlinear) in this or that computer installation. This relationship may be quite varied and depends on the type of problems to be solved. Consequently, the analog computers are complemented with computing elements of different types to be used in place of the standard elements. Besides, an analog computer has general-purpose elements (comprising the control, measuring, power supply and coefficient-settling systems).

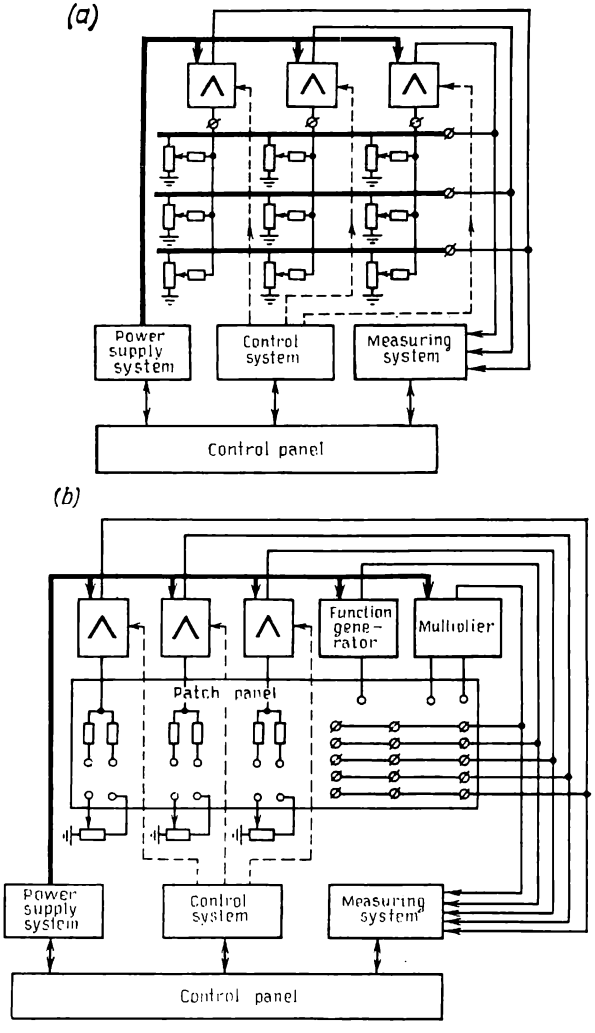


Fig. 6.17

The control system of an analog computer employs relay-contact logic providing the basic operating conditions of a computer installation involving problem setup (setting the initial condition, coefficients, etc.), problem solution (integration of differential equations, simulation of algebraic relationship, etc.), the HOLD condition that permits checking the values of all coordinates at a given moment

of time, the RESET condition when all integrators are reset to the specified initial conditions. The HOLD condition makes it possible to use a high-precision timer to synchronize the changes between conditions with time readout. This timer can be also used to perform various switching operations as a function of time.

The measuring system of an analog computer provides for connection to the output of each computing element of voltmeters (usually digital) and oscilloscopes (displays) with a screen persistence of several seconds (at the sweep time of up to 100 s). The display units can operate on a multichannel basis so that the sweep rate is fast enough to permit simultaneous presentation of several curves. These devices can send control signals back to the computer for repetitive solution of the problems to facilitate observation as well as furnish time marks and provide for amplitude measurements. Repetitive solution of the problems is called repetitive operation.

The power supply system is essential to the operation of an analog computer insofar as the voltage amplitude is the basic information parameter. For this reason, the supply voltage of the operational amplifiers and the reference voltage fed to the function generators are subject to regulation. For supply voltage regulation, use is made of temperature-stabilized reference diodes. The reference voltage in the analog computer is maintained constant accurate to within thousandths of per cent. This permits the use of highly accurate compensation methods of measurement when setting the initial conditions and reading the computation results.

The coefficient-setting system determines to a large extent the scope of problems to be solved on a particular computer installation since the end results would be difficult to obtain if it took much time to set the transfer coefficients of the amplifier, check them and adjust during operation.

A combined approach is taken in adjustment of the transfer coefficients, whereby the input resistors and sometimes capacitors are adjusted in a discrete manner and the voltage divider is made continuously-variable, making it possible to obtain fractional values of the coefficients. As a general rule, the resistors and capacitors are switched manually. Adjustment of the voltage dividers may be accomplished by three methods: (a) manual, by means of indicating meters and potentiometers; (b) manual, by means of numbered dials; (c) automatic, by means of electromechanical servo systems.

The last concept is demonstrated by Fig. 6.18 which shows a typical arrangement comprising a motor (M), an amplifier (A) and a potentiometer transducer (P). This circuit is linked to a system of electromagnetic clutches, $EC1$, . . ., EC_m, each of which rotates the wiper of a voltage divider in one of the computing elements following application of an appropriate control signal.

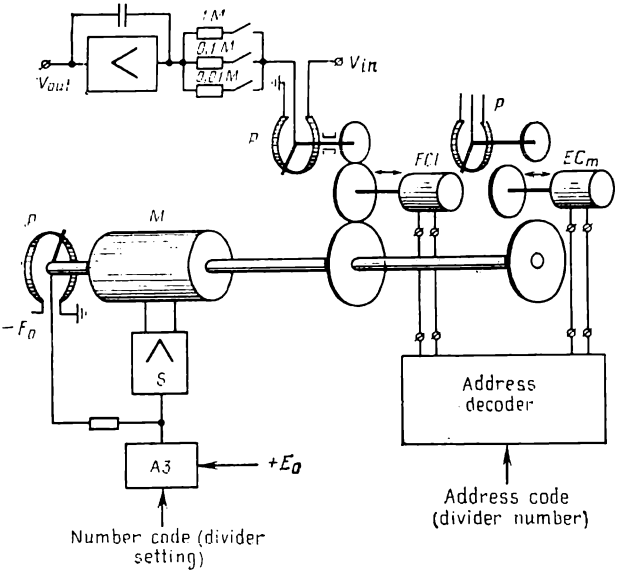


Fig. 6.18

Referring to the diagram, the values of coefficients can be set in the digital form by means of a special keyboard or a digital computer with subsequent conversion to the analog form with the use of a current converter A3. The electromagnetic clutches act as storage devices by holding the introduced coefficient values after being disengaged from the system. A signal which counterbalances the coefficient value set in the current converter is applied directly from the voltage divider being adjusted (after the required switching of the reference voltage), making it possible to cut down the labour requirements and considerably improve the setting accuracy by automating the coefficient-setting process.

The voltage dividers with numbered dials are particularly suitable for selection of the parameters of a particular system on the basis of the results yielded by the investigation of its model. A disadvantage of these voltage dividers is that they take up too much space on the front panel of the computer installation. Besides, they are costly and have insufficient setting accuracy (around 1%). Manual setting of voltage dividers by means of meters or potentiometers is the most cost-effective method of adjustment but its use is limited to small-scale model setups or to simulators comprised within a larger research complex. This latter application is typical of the analog computers.

Design features and types of problems solved on analog computers. Analog computers can be used as purely computing machines (with frequently changing problems) and as research tools (when the problems are changed comparatively infrequently). Both applications are successfully suited by large computer installations characterized by automatic setting of coefficients and other innovations and by installations comprising several small machines operating in parallel and having various subsidiary devices which perform specific functions. For these applications, use is made of the following machines:

—a type АФБ-1 small-size portable analog computer with six tube amplifiers rated at 100 V, one multiplier and one function generator;

—a type МН-7 (МН-7М) small-size desk-top analog computer with 18 tube amplifiers rated at 100 V and a total of eight multipliers and function generators;

—a type АВК-31 small-size desk-top analog computer with 12 transistor amplifiers rated at 10 V and a total of four multipliers and function generators;

—a unitized low-power analog computer of the "Analog-1" type with 20 high-precision tube amplifiers, one multiplier and one function generator.

All the above-listed machines feature additional diode elements for simulation of typical nonlinear functions and have facilities for parallel operation in applications involving the use of several computers. In small computers, coefficient setting is accomplished by means of meters or potentiometers.

There are also machines featuring automatic coefficient-setting systems and removable problem boards (prepatch panels) permitting quick substitution of problems. These include the following:

—a type ЭМУ-10 medium-power analog computer with 48 tube amplifiers rated at 100 V, four function generators and four multipliers;

—a type АВК-2 (2) medium-power analog computer with 68 transistor amplifiers rated at 100 V, ten multipliers and ten function generators;

—a type МН-17 high-power analog computer with 160 tube amplifiers rated at 100 V and a total of up to 80 multipliers and function generators (with two patch panels);

—a type МН-14 very high-power analog computer with 356 tube amplifiers rated at 100 V and an optional combination of up to 160 function generators and multipliers.

These machines have a rack-type construction, high-precision amplifiers and feedback networks and, apart from the electronic multipliers and function generator, include associated electromechanical systems of different types.

In the Soviet Union, a vast number of various computers are used by the power organizations for planning, designing and operation of the power systems. The problems being considered are of a varying nature but, as in other industries, the bulk of the problems is connected with automatic control and management.

Of particular importance are the problems associated with the development and evaluation of the facilities for controlling the electromechanical transients emerging in the power systems as a result of various disturbances. These problems can be conventionally divided into two types, i.e. those associated with the control of the prime movers of synchronous generators and those associated with controlling their excitation. Both types of problems are investigated in relation to the elementary power system with subsequent upgrading to a more complicated scheme which is a closer approximation of the real one. However, the system ordinarily comprises three or four equivalent generators.

The important factors to be taken into account when investigating the problems associated with control of prime movers are the typical nonlinearities of the control system, dead zone and backlash. These parameters have a strong effect on the ability of the turbines to take up load in the event of an emergency reduction in frequency in the power system and to maintain the specified power level over weak ties. The limiters are essential for ensuring the transient stability of power systems by applying emergency control to the steam turbines. Such nonlinearities cannot be incorporated in the usual methods used in the analysis of automatic control systems (such as the describing function method). The governing consideration here is the required degree of particularization, i.e. the necessity of taking into account the various factors affecting the processes under investigation. Fig. 6.19 exemplifies a model of a prime mover intended for evaluation of its control system.

The model presented in Fig. 6.19 simulates the following:

(1) equivalent servo motor *S* is represented by integrator *A2*, the slide valve, by amplifier *A1* and the direct feedback element, by amplifier *A3*. In this arrangement, limiter *L1* imposes limitations on the rate of displacement of the servo motor in opening and closing the valves (ξ_{max} and ξ_{min}) while limiter *L2* imposes limitations on the run of the servo motor (μ_{max} and μ_{min});

(2) the relationship between the valve opening and the run of the servo motor (represented by function generator *FG1*) and the equivalent entrained steam of the turbine *T* between the control valves and the control stage (simulated by amplifier *A4* connected as an aperiodic element);

(3) the swing equation of the synchronous generator *G* based on the assumption of constancy of the e.m.f. behind certain reactance and applicable to operation of the unit over a power line to infinite

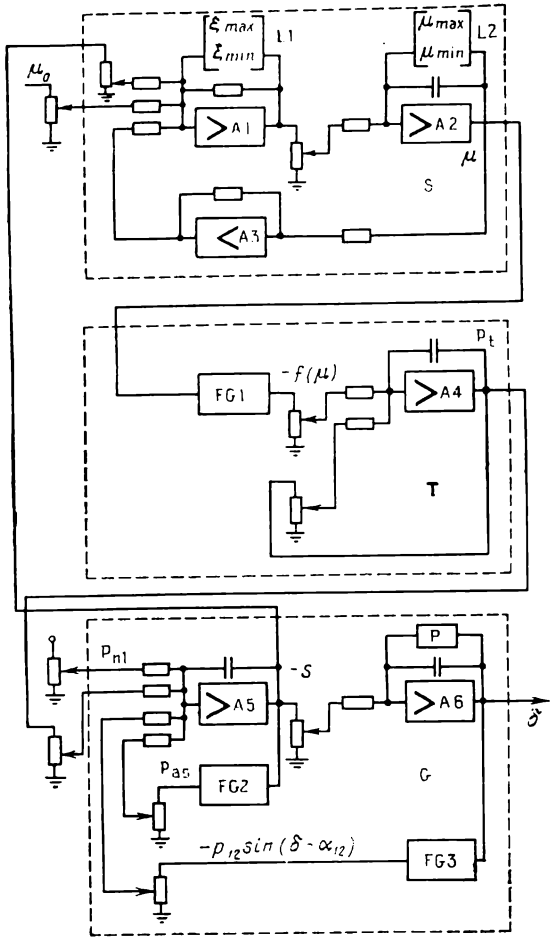


Fig. 6.19

buses. The equation is presented in its usual form as follows:

$$\frac{\tau_J}{\omega_s}\frac{d^2\delta}{dt^2}+P_{as}(s)+P_{12}\sin(\delta-\alpha_{12})=P_t-P_{nl} \qquad (6.20)$$

where τ_J is the inertia constant; ω_s is the synchronous speed; δ is the power angle; α_{12} is the loss angle; P_{12} is the maximum of power angle curve; $P_{as}(s)$ is the asynchronous power; P_t is the turbine power; P_{nl} is the no-load power.

In this case, the function generator *FG2* which simulates the component P_{as} is connected to integrator *A5* and a special autocycler *AC* is connected to integrator *A6*, making it possible (with the function

generator *FG3* properly adjusted) to reproduce a sinusoidal function within the range of $\pm 2\pi$ and to investigate the processes during asynchronous operation.

When investigating the problems associated with the control of excitation of synchronous generators, the model should represent in more detail the processes taking place in their rotor circuits so that a portion of it which is related to the generator and the transmission system is usually configured in accordance with the Park-Gorev equations with a number of assumptions. So, to reduce the amount of equipment, the models use passive networks introduced in the feedback circuits of the operational amplifiers to allow complex operator expressions to be reproduced by means of a single amplifier. A representative model of one of the excitation control systems is shown in Fig. 6.20. This model is used to simulate the following:

(1) the equivalent dynamic characteristics of the regulator and the excitation system based on the assumption of forced regulation using the derivatives of angle δ (the amplifier *A1* and its output passive networks);

(2) two equivalent circuits in the direct axis (including the circuit of the excitation winding) and one circuit in the quadrature axis (amplifiers *A3* and *A4* with complex (composite) feedback circuits);

(3) the swing equation of the unit connected through a loss-free line to the buses of infinite power based on the assumption of constancy of mechanical power (P_t = const) simulated by means of amplifiers *A10* and *A11*.

In addition, the system incorporates function generators and multipliers for computation of the generator current components in axes d and q as well as the full electromagnetic power of the generators P_e and the absolute value of its terminal voltage V as an input signal for the voltage regulator.

With varying degree of particularization, the setups of this kind are widely used in the problems connected with evaluation of stability and selection of control facilities for the power systems. However, a large amount of hardware is required for simulation of relations between the generators in a complex power system. Each relationship requires the use of a minimum of two multipliers and two function generators in a coordinate conversion setup, plus the equipment required for simulation of the parameters of power lines. Therefore, the investigation of complex power systems is frequently based on the assumption of voltage constancy behind certain reactance x so that with m generator stations simulation of m equations of motion of the following form is required:

$$\frac{\tau_{Ji}}{\omega_i} \cdot \frac{d^2\delta_i}{dt^2} + \sum_{\substack{i=1 \\ i \neq j}}^{m} P_{as}(S_{ij}) + \sum_{\substack{i=1 \\ i \neq j}}^{m} P_{ij} \sin(\delta_{ij} - \alpha_{ij}) = P_{ti} - P_{ii} \qquad (6.21)$$

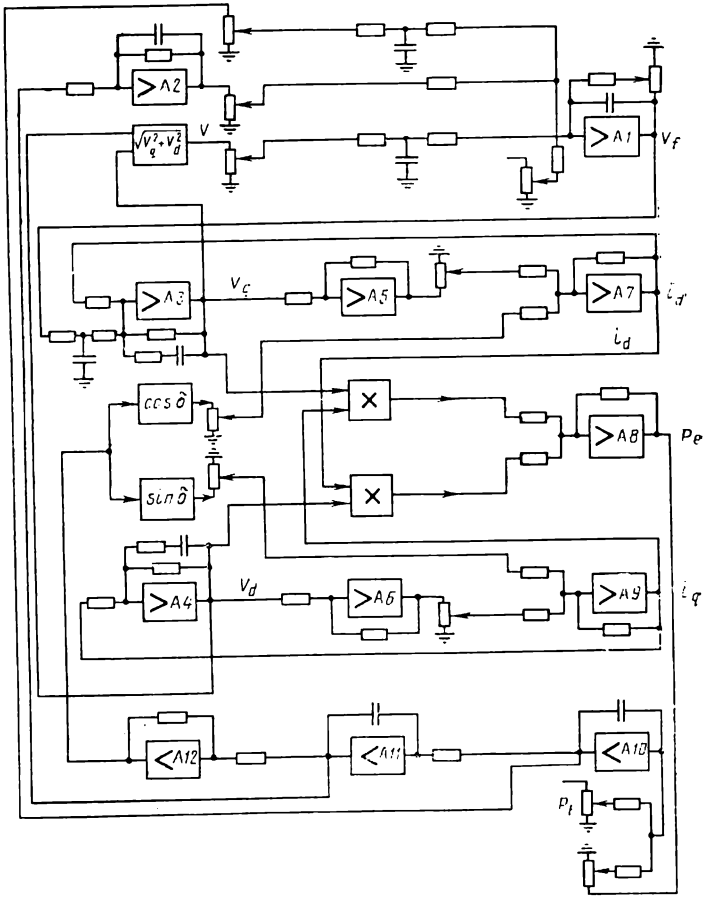


Fig. 6.20

A three-machine system shown in Fig. 6.21*a* is the basic model of a complex system and is successfully used for investigation of the transient steady-state stability and asynchronous operation. When set up on an analog computer, the model of a three-machine system looks like a triplicate model of an elementary power system supplemented with the networks for relative angles and slips (Fig. 6.21*b*). This model is used to simulate the following:

(1) loading of individual power lines under the normal (quiescent) operating conditions. The model is set up for these conditions at $s_i = 0$ when the differential swing equations like (6.21) degenerate into algebraic equations. The system is usually brought to ope-

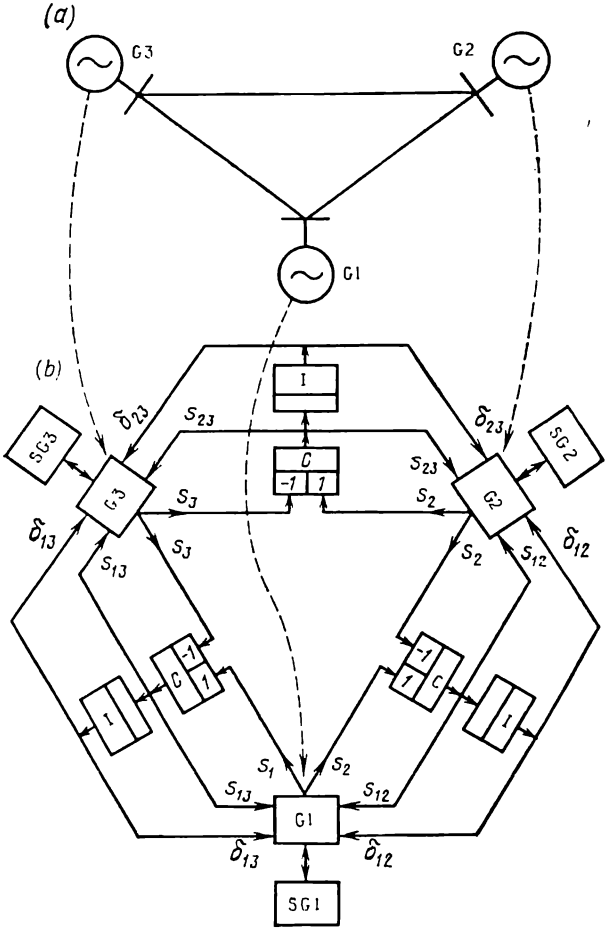


Fig. 6.21

rate under steady-state conditions by the operator who sets the required load parameters in the models of isolated power units. In this case, the models of speed governors are of considerable help to the operator;

(2) behaviour of the power units when the system is disturbed by load shedding, disconnection of generators or short-time reduction in the amplitude of power angle curve simulating the short-circuit condition;

(3) behaviour of the power unit as in (2) above with simultaneous simulation of the measures aimed at improving stability, such as

disconnection of a number of generators, emergency control of the prime mover, etc. In case of necessity, the model of one of the generators may be set up in accordance with the Park-Gorev equations and connected to the models of other power units through the coordinate conversion circuits.

The need for solution of algebraic equations of flow distribution which are solved in this case together with the basic (differential) equations has led to such an order of solution in which integration begins with setting zero initial conditions and is accompanied by setting the required values of generation at the stations with absolute slip monitoring. This makes it possible to obtain carefully balanced initial conditions. Following this, the disturbances are introduced into the system and the investigation of the transient process of interest begins.

The choice of time scale for the models being considered is governed by the fact that multipurpose analog computers can easily simulate the natural frequency of 1 Hz characteristic of the electromechanical transient processes in the power systems. Therefore, the models are customarily set up on a real-time basis. In cases where an extremely high dynamic accuracy is required the process may be slowed down 5 to 10 times.

The practical importance of multipurpose analog computers for solution of the problem concerned with control of the operating conditions of power systems is not very high. Aside from the common difficulties stemming from the dependence of the amount of equipment used on the complexity of the systems, the use of analog computers involves additional difficulties connected with the effect of programmed controllers and also with the complexity and insufficiently representative character of the problem setup process, etc. The former of these difficulties is overcome by using hybrid computing systems and the latter, by the use of special-purpose computers.

Hybrid computing systems and their applicationin power industry. Hybrid computers are frequently expanded into hybrid computing systems in two radically different approaches. The first approach is to combine a multipurpose analog computer and a multipurpose digital computer and the second is to provide a complete computer installation consisting of an analog and digital sections. The first approach is now more popular and ordinarily involves the use of a digital minicomputer and a specially adapted analog computer integrated through ADC and DAC converters. In either case, the functions of the digital and analog equipment can be shared as follows:

—analog simulation, digital control;

—analog simulation of fast processes in a system, digital simulation of slow processes;

—combination of the digital and analog methods on the operations level.

For practical applications, the simulation of the discrete control devices (by means of the digital subsystem of an analog computing system) of the system being simulated, including a control digital computer, has proved to be of major importance. The EAI-8 900 system of this type developed by the US company EAI is employed by a number of power organizations. The analog subsystem of the EAI-8 900 system consists of 156 integrators, 180 inverters and 300 summers and the digital subsystem comprises a 32-bit digital computer with a storage access time of about 2 ms. In 1967, it was used in investigations of the automatic control systems of the nuclear power stations of Great Britain. A study was conducted at that time to compare the time and hardware requirements of a hybrid computing system and a high-speed digital computer of the IBM-360/75/50 type used for the same purpose. As it turned out, the hybrid computing system was 500 times as fast and 100 times as cost-effective as the digital computer.

The Soviet-Yugoslav system ГВС-100 which has an integrated-circuit design features an analog subsystem with sufficiently high-speed amplifiers rated at 10 V with a maximum bandwidth of up to 800 kHz, a digital subsystem based on a 32-bit digital computer with a storage access time of about 1 μs and a communication facility (data link) comprising a digital-to-analog converter with a conversion time of 1 μs, a multiplying digital-to-analog converter with a conversion time of 2 μs, three analog-to-digital converters with 32-channel commutators as well as a large amount of other equipment.

A distinguishing feature of the analog subsystem of the hybrid computing system is the extensive use of parallel logic circuits, including eight 4-bit flip-flop registers, two decimal counters, 48 coincidence circuits for a different number of bits, etc. Besides, there are 20 amplifier comparators with a settling time of 0.04 μs, a large number of various relays and other devices.

Logic elements are interconnected with the digital components of the installation through four groups of 16-bit communication lines, including control lines for transmission of digital data to the parallel logic from the digital computer, indication lines for transmission in the opposite direction, interrupt lines for transmission of interrupt signals to the appropriate register of the digital computer from the analog subsystem, sensitivity lines allowing the parallel logic to change the contents of the sign bit of the register which is an accumulator of the arithmetic and logic unit of the digital computer, thereby enabling execution of the conditional transfer operation. In this way, possibilities are created for fully automatic processing of the problem on the analog computer with the further strategy of investigation determined on the basis of earlier computations.

By way of an example, consider how the type ГВС-100 system is used to determine the limits of transient stability of a three-machine power system. The algorithm of solution of this problem is illustrated in Fig. 6.22. It provides for setting a certain initial condition and checking it by reading the parameters of the analog computer by the digital computer through an analog-to-digital converter. Following this, disturbances like short circuits gradually increasing in duration are introduced in the system (for each individual power line).

The progress of the transient process and its outcome ("stable—unstable") are checked by means of the amplifier comparators and this information is transmitted to the digital computer. After determining the duration of the short-circuit condition which is marginal from the standpoint of synchronous transient stability of each power line, the least duration, $t_{sc\ min}$, is selected and is henceforth taken as the marginal criterion of synchronous transient stability*. The ГВС-100 system can also automatically investigate a number of operating conditions and specify the least $t_{sc\ min}$ in their entirety.

Investigations may be conducted when the system operates on a different time scale ($m = 0.1$; 100; 1 000). The time scale $m = 100$ has proved to be the most practical inasmuch as the difference between solutions as compared to real time does not exceed 5-6% of the maximum time $t_{sc\ max}$, whereas at the time scale of $m=1\ 000$ the discrepancy increases to 15-16%.

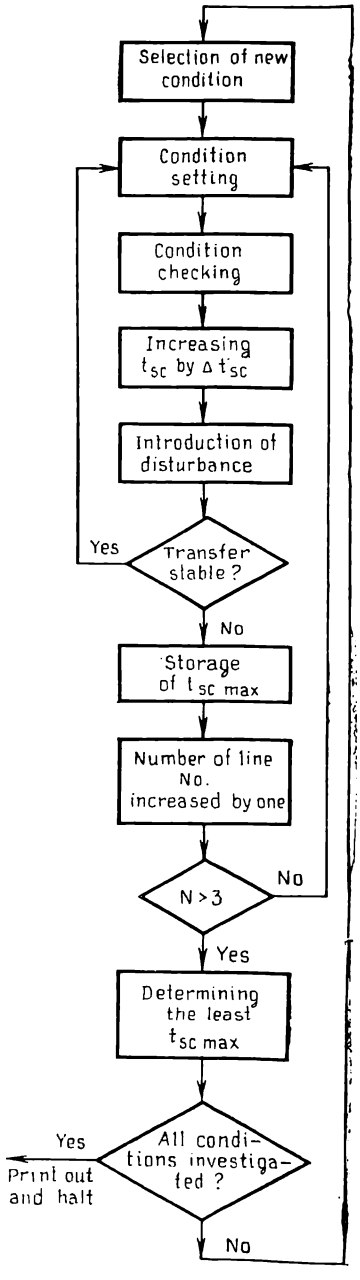


Fig. 6.22

* More specifically, the marginal criterion is understood as the excess of $t_{sc\ min}$ over the specified time of short circuit isolation by the main protection equipment.

The adopted algorithm is characterized by the fact that the initial condition is set each time the time t_{sc} is increased. This approach has been necessitated by the fact that specialized electronic high-speed servo systems are used for setting the transfer coefficients of the operational amplifiers in the ГВС-100 system. In this case, the entire operation involving setting and checking the operating conditions takes 170 μs and it is not practical to execute it out of cycle. By way of comparison, note that when conducting a similar investigation on a hybrid computing system with electromechanical servo systems this operation takes several seconds to perform, and, naturally, is brought out of cycle, i.e. executed only when setting the new condition.

In the system under consideration, it was necessary to compute several swing cycles which spanned 3-5 s in real time in order to define more exactly the nature of the dynamic transfer, and this took 30 to 50 ms of machine time on the selected time scale. In this case, the operate time of electronic relays which introduced the disturbance was of the order of 1 μs, constituting a negligible quantity with respect to the duration of the short-circuit conditions being investigated (i.e. of the order of 0.2 s in real time and 2 ms in machine time, respectively). Therefore, the disturbances were introduced without interrupting the operation of the system so that a full investigation of loading condition required about 0.5 s with two to five variants of short-circuit duration for each of the three lines, the time taken by preparatory operations not exceeding 10% of the integration time proper.

6.4. Special-Purpose Analog and Hybrid Computing Systems Used in Power Systems and Interconnections

The comparative analysis of the properties of parallel and sequential structures has shown that the specialization of computing aids with parallel structures leads to their effective utilization. This is due to the strict relationship between the scope and nature of the problem to be solved on the one hand and the number and functions of the computing elements on the other. In this connection, specialization makes it possible to minimize the amount of unused equipment and adapt the computing elements in the most effective way to the execution of specific functions.

The latter consideration is of particular importance to the power industry. Modern multipurpose analog computers are, in effect, oriented towards the solution of ordinary differential equations describing systems with valve elements (a change in their output does not affect their input). Such elements are used in vast numbers in automatic control systems so that their theory is sometimes called

"one-way mechanics". Investigation of the systems with elements which do not possess valve-like properties gives rise to more complex algebraic relations resulting in the appearance of closed loops in the model. The creation of such loops in the analog computers requires a large amount of equipment.

Nevertheless, the equations of interest can be solved by linearization and the attendant loops may be balanced without using the amplifiers at all. For such computations, use may be made of ladder networks composed of such circuit components as resistors, capacitors or reactors. This approach may be regarded as a direct-analogy simulation when solving the problems concerned with controlling the operating conditions of the power systems. However, it can be extended to include indirect analogs. Multipurpose computers do not provide for this method of solution so that it cannot be implemented on a large scale. But it can be easily and effectively implemented by means of special-purpose computers.

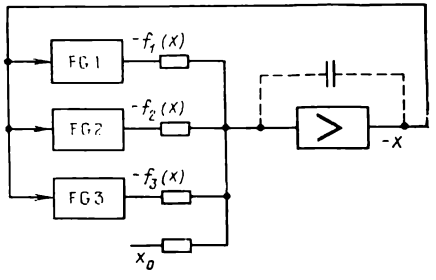


Fig. 6.23

There is another way of improving the efficiency of special-purpose analog computers when dealing with nonlinear problems, and it consists in providing function generators that can be easily readjusted to generate a specific function. With the limited class of functions, this allows one to obtain better results than with general-purpose function generators. The method of equation solution still remains common to the multipurpose and special-purpose machines in that it requires the setting-up of a circuit (Fig. 6.23) in which the operational amplifier acts as a balancing element ensuring the equality of the left- and right-hand sides of the equation under all conditions, so that the higher the amplifier gain the more carefully maintained is the specified equality.

This factor may be regarded as a peculiar property of the networks with operational amplifiers, allowing the algebraic equations to be solved by the analog computers using specific non-algorithmic methods which eliminate the necessity for special methods of computation. But, insofar as the operational amplifier is a physical entity with unambiguous dynamic properties, the network shown in Fig. 6.23 may become unstable under certain conditions and turn into a continuous-wave oscillator. To avoid this, the balancing amplifier frequently incorporates a capacitor shown in Fig. 6.23 in broken lines. In this case, the solution of an algebraic equation may be regarded as a degenerated solution of a differential equation as

can be ascertained by comparing the circuits of Figs. 6.23 and 6.1*b*.

Consequently, algebraic equations are solved by the analog computer quickly enough (for all practical purposes, instantly). This ability has stimulated the production of special-purpose analog computers of two types. Special-purpose analog computers of the first type are used for computations connected with efficient load distribution in the power systems while the computers of the second type are used for computations involving electromechanical transient processes in the power systems. At the same time, the special-purpose analog computers of both types are used for solution of problems pertaining to flow analysis of electric networks.

Computers for efficient load distribution in power systems. These machines are used either as part of the automatic load frequency control systems or as dispatcher's aids.

Such machines are used to solve problems on the basis of a system of algebraic equations of the form:

$$\frac{\alpha_1 b_1}{1-\sigma_1} = \ldots = \frac{\alpha_i b_i}{1-\sigma_i} = \ldots = \frac{\alpha_n b_n}{1-\sigma_n} = b_0 \qquad (6.22)$$

under the following conditions:

$$\sum_{i=1}^{n} P_i = \sum_{i=1}^{m} P_{0i} \qquad (6.23)$$

$$b_i = f_i(P_i) \qquad (6.24)$$

$$\sigma_i = \psi(P_1, P_2, \ldots, P_n; P_{01}, P_{02}, \ldots, P_m) \qquad (6.25)$$

where α is a coefficient allowing one to take account of the specific operating conditions of the station within the system (replaced by λ in the case of hydroelectric power stations); b_0 and b_i is the incremental fuel consumption for the entire system and for the associated power stations, respectively; $1-\frac{1}{\sigma_i}$ is the penalty factor; P_i is the generation capacity; P_{0i} is the power consumption.

The calculations are based on the assumption that any total load of the system (6.23) corresponds to a certain value b_0 which satisfies (6.22) provided conditions (6.24) and (6.25) are observed. In this case, the computer installation can be regarded as consisting of two independent units operating simultaneously within the parallel structure of the installation, i.e. a unit for computation of the optimal value of P_i for each station and a unit for computation of σ_i.

The structure and composition of the first unit (Fig. 6.24) is in full compliance with the method of solution of nonlinear algebraic equations on analog computers considered above (the only difference being that multiplication is performed in addition to the generation of a nonlinear function).

Assuming that the value of incremental rate b_0 of the system is specified, then the values $P_1, P_2, \ldots, P_m$ will be obtained at the outputs of elements *1*, *2*, . . ., *m* after conversion which is the reverse of (6.24). These values are simultaneously fed to the output of the unit and to the input of the balancing amplifier, where they are summed (algebraically) with the load values preset in the computer for all the nodes of a power system without exception.

It becomes apparent that conditions (6.22) through (6.25) are satisfied if the resultant closed loop is in a steady state. Then we shall find the value of σ_i which in the general case represents a nonlinear function of the load for the power lines. To do so will require a preliminary computation of load flow in the network. Various indirect methods serve as a means to this end. In the case of the special-purpose analog computers, use is made of a direct method (albeit approximate), whereby the machine is used to set up a resistorized model of the network used for direct flow analysis of real power in the system. Fig. 6.24 illustrates this method which has found its utilization in practically all machines of this kind.

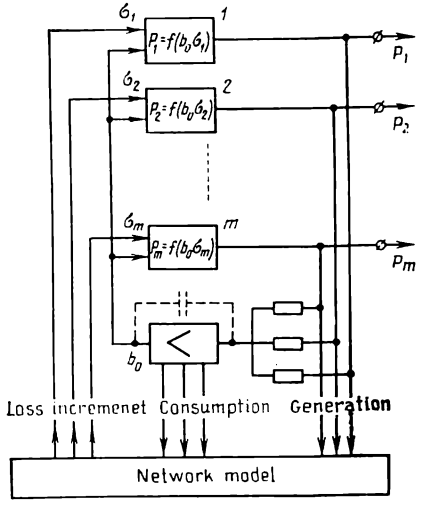


Fig. 6.24

Special-purpose computers make it possible to take account of isoparametric conditions applicable to the specified daily average consumption of the energy carrier. To this end, it is necessary to:

(a) use a function generator to obtain the current power P_i of a station as a function of energy carrier consumption B_i;

(b) produce at the load setting terminals a function of time corresponding to the predicted load curve for the system;

(c) store the integral of energy carrier consumption $\int Bdt$ for the period of required duration and compare it with the specified value.

For representing the load curves as well as the characteristics of relative increments b_i (P_i), it is practical to use nonlinear elements with a triangular current characteristic (see Fig. 6.13*c*).

A number of machines have been developed along these lines in this country and abroad (to mention Ekran-7 which performs integration of energy carrier consumption and РЭР-2 which utilizes non-

linear elements). Although these machines suited the needs of dispatch control, they proved to be less effective in terms of flexibility (adaptability to the changing layout of the network) and input/output capabilities than the digital computers employed at the dispatch control centers as computing aids for efficient load distribution.

Computers for evaluation of electromechanical transient processes. The growth of the power systems was accompanied by the lowering of the stability margin of the trunk lines. Stability control schemes have emerged as a counterbalance to this problem, and this involved a large amount of computations. After many possibilities have been studied, it was found practical to analyze the processes on a fast time scale. Modern digital computers which are in wide use today are unable to do that even on a real-time basis (for instance, the IBM-360/65 computer which has a speed of 600 000 operations per second takes more than 8 s to simulate a process 1 s in duration involving a system of 15 equivalent generator stations with 50 network nodes). As a result, more and more development engineers looking for higher computing speed turn to the parallel structures realized by means of analog computers.

Three types of devices are used to simulate electric networks as direct-analogy models but the organization of the computing process is different in each case. The devices of the first type provide a parallel structure only for the network model, whereas the generator stations are simulated by analog elements on the sequential principle.

The devices of the second type have a purely parallel structure based on the analog models of standard generators connected to the computing model of an a-c network and permit the use of a digital computer to determine the strategy of problem solution with the aid of the model. The devices of the third type are hybrid in principle, since the integration of the analog and digital computers involves some portion of the process directly on the operations level. Following is a brief discussion of these devices.

Sequential organization of the computing process in a system simulating an electric network is realized in a machine of the АМЭС type developed by the Armenian Research Institute of Power Engineering (ArmNIIE) and intended for solution of the equations of motion of synchronous generators of the form

$$\frac{\tau_i}{\omega_s} \cdot \frac{d^2\delta_i}{dt^2} + K_s s_i = P_{ti} - P_{ei} \qquad (6.26)$$

where K_s is the self-regulation (damping) coefficient; P_e is the electric output of the power unit.

The setup shown in Fig. 6.25 comprises an a.c. network analyser (*NCM*), voltage sources in the form of synchro phase shifters

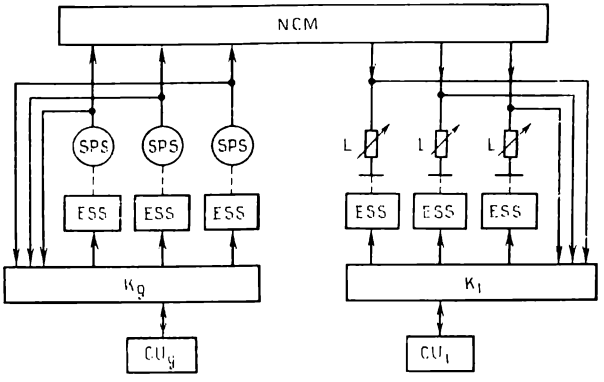


Fig. 6.25

(*SPS*) and loads (*L*) representing resistance and inductive reactance with provisions for adjustment. Use may be also made of nonadjustable loads in the form of permanent shunts.

All voltage sources and adjustable loads are provided with electromechanical servo systems (*ESS*) connected through the commutators (C_g and C_l) to computing units (CU_g and CU_l) whose inputs are fed through the commutators with signals required for determination of power in the circuit of the respective voltage source or load. Computing units CU_g perform numerical integration of equation (6.26), and the associated operations of summing, multiplication by a constant coefficient, etc. are performed by the analog rather than discrete computing elements.

The machine operates by steps. At each step, the computing unit is connected to the appropriate generator station, its terminal power P_{ei} is measured, the imbalance of powers P_{ti}-P_{ei} is determined, an increment in angle at the given step of integration $\Delta\delta_i(t)$ is calculated and an appropriate signal is furnished to the electromechanical servo system. Following this, the computing unit switches over to the next $(i + 1)$th generator station and the electromechanical servo system of the i-th station is disabled. As a result, the value of angle δ_i set by the system remains unchanged until the next step of integration. In this way, the electromechanical servo system operates as a storage device. Computing unit CU_l operates in a similar manner performing solution in accordance with the algorithms that provide for the desired relationship between power and voltage, etc.

As with any sequential structure, the number of computing units required for integration remains unchanged despite the expanding scope of the problem. The only parameter that will increase is the

integration time T which, when computed for one second of time of the original system with N generator stations, will constitute

$$T = (N/\Delta t_i)\, t_{op} \tag{6.27}$$

where Δt_i is the step of integration and t_{op} is the mean time of execution of one operation for computation and setting of $\Delta\delta_i$.

At the same time, the computation of load flow as part of the overall process of numerical integration is practically instant at each step of integration. Attempts to increase the number of generator stations or network elements in excess of that provided by the machine will immediately increase the demand for more equipment.

The second type of special-purpose computer installations intended for integration of synchronous machine equations are characterized by the use of analog computing devices operating in parallel. Such installations are constructed from electronic computing elements or computing elements utilizing electromechanical servo systems. The complete installations are called *automatic computing models of power systems* and the models of generators which they embody are called *automatic generator stations.* Such machines are known to have been developed in the USSR (by the "Energosyetproyekt" research institute), Japan (by the "Yokahawa" company) and in other countries.

The operating principle of automatic generator stations can be summarized as follows. Electromechanical servo systems with large gain in negative feedback for the speed of output shaft perform integration with sufficient accuracy. They are used to compute the value of both integrals of the swing equation or only of the second integral (if so, the value of the first integral is computed by an electronic element). In both cases, the output shaft of the servo system mounts (as was the case with the machine of the АМЭС type) a synchro phase shifter used as a voltage source at the output of the generator station. At the input of this station, a power transducer is used to determine the value of imbalance of P_t-P_e and subsequent operations for its integration are performed.

In some cases, the automatic generator stations take account of the effect of speed governors which are simulated by special elements (usually electronic). Moreover, the design of these elements allows one to reproduce the effect of the excitation regulators, but these elements are complex and have little practical use. But the main drawback of the automatic generator stations is low speed.

In this respect, the best result obtained so far has been a speed-up of 50 times as compared to real time. In the majority of cases, however, this time scale has proved to be unsatisfactory as it does not make possible to obtain data required during operation, e.g. when selecting the adjustment of the stability control schemes of the power systems, etc. For this reason, great interest is shown in special-purpose

computers utilizing high-speed electronic elements and called *electronic generator stations.*

The basic principle underlying the operation of these computers is that the setups typical of the analog computers (see Figs. 6.19 and 6.20) are used for integration of the differential equations of a synchronous machine and for conversion of the resultant values of V_g and δ into the amplitude and phase of the alternating current supplied to the network analyser, so that a system analogous to the automatic model is obtained with much higher speed. If such a system operates in real time and the network analyser has a frequency of 50 Hz, it is suitable for connection of actual control and monitoring equipment. This gives one an impression that the capabilities of this setup correspond to the capabilities of the electrodynamic (physical) model, but it is not true.

Indeed, regardless of the type of generator stations, the system of currents and voltages in the network analyser remains asymmetrical, or single-phase. For simulation of various faults, in the original symmetrical three-phase system, the model uses various equivalent circuits, and the power and the corresponding torque measurements across the generator shaft are taken only in accordance with the positive sequence. This eliminates a number of components affecting the process and the machine is used as a computing aid in accordance with the established practice.

In principle analog computing techniques can be also used to set up a three-phase model of a power system with account for the processes taking place in the generator but it has not been done yet due to the difficulties involved. When using a single-phase model, two simplifications can be made as a matter of course by:

(1) disregarding the electromagnetic phenomena associated with switching in the generator stator circuits and in the network which is a continuation of this circuit. In this case, the network analyser is regarded as a device for simulation of load flow in the system under the steady-state and transient conditions and for solution of algebraic equations describing the load flow. At the same time, natural electromagnetic processes which occur in the model as in any *RLC* system should be suppressed and the current frequency in the network model should not be bound by any relationships to the current frequency in the original system so that it could be selected at will;

(2) departing from the full system of the Park-Gorev equations. In the case of generators which are sufficiently remote from the location of a short circuit, it would be well to reproduce the nature of the transients on the assumption of constancy of the e.m f. behind certain reactance (e.g. X' or close to it). This e.m.f. is maintained due to the electromagnetic processes in the rotor circuits and the processes associated with the effect of the voltage regulators. Without

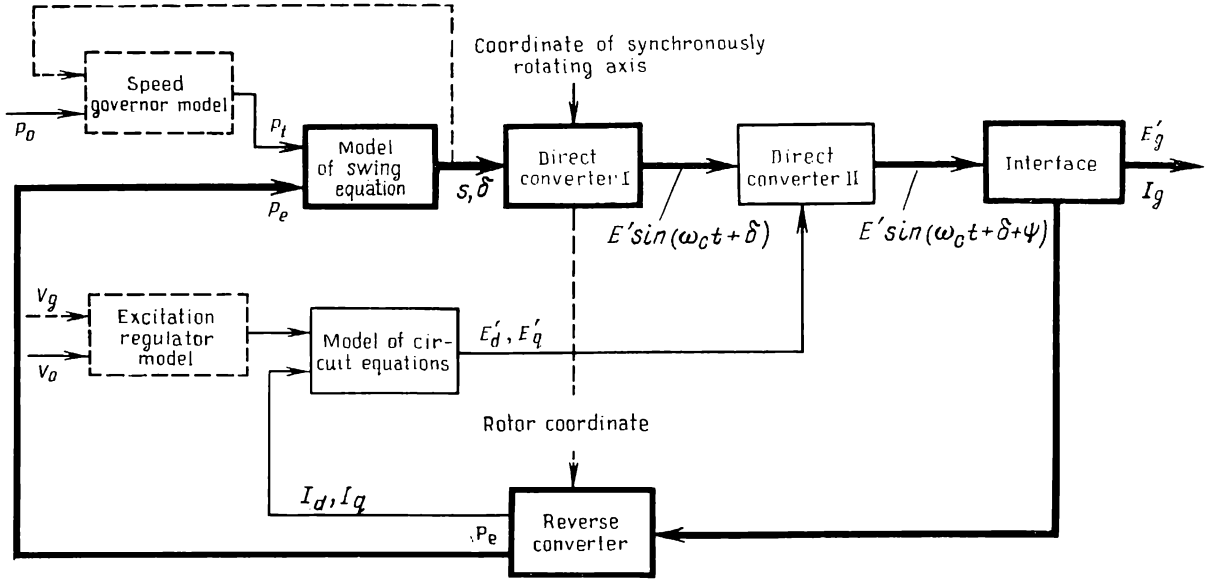

Speed governor model
P_0
P_t
Model of swing equation
P_e
S, δ
Coordinate of synchronously rotating axis
Direct converter I
$E'\sin(\omega_c t+\delta)$
Direct converter II
$E'\sin(\omega_c t+\delta+\psi)$
Interface
E'_g
I_g
V_g
V_0
Excitation regulator model
Model of circuit equations
E'_d, E'_q
Rotor coordinate
I_d, I_q
P_e
Reverse converter

Fig. 6.26

simulating these processes, the calculation of motion may be limited to solutions (6.21) or (6.26).

But whenever more accurate results are required, it is necessary to take account of the processes that take place in the rotor circuits as well as the effect of the voltage regulators. Such stations are called *complete generator stations* while the stations set up in accordance with the swing equation are called *simplified generator stations*. Both the complete and simplified generator stations may be represented by a common block diagram (Fig. 6.26) in which the blocks shown in thin lines represent the exclusive components of the complete stations.

The electronic generator stations are provided with converters of the direct and reverse type. Direct converters are intended to transfer the results of solution of the given equations to the a.c. model. Converter *I* generates a sine signal shifted by an angle δ relative to a certain voltage (coordinates of a synchronously rotating axis) which is common to the machine. Converter *II* effects additional conversions of this signal for a more detailed account of the processes taking place in the rotor circuits. Converter *II* is not installed in the simplified generator stations since their terminal voltage is assumed to be constant and is changed only by the operator when setting the operating conditions.

In their turn, reverse converters may be also of two types. When used in a complete generator station, they are intended for discrimination of current components $I_{\bar{d}}$ and $I_{\bar{q}}$ of a.c. current in the circuit of the electronic generator station in the form of the d.c. voltage proportional to these components and for computation of the generator shaft power on the basis of the current and voltage components. No discrimination of the currents $I_{\bar{d}}$ and $I_{\bar{q}}$ is required in a simplified generator station and, with the generator voltage being constant, the generator shaft power may be determined by using the signal proportional to the resistive current component which is more liable to detection than the signal proportional to the power.

Network analysers and interfaces. The devices which serve as interfaces with the network analysers ordinarily consist of two related elements, i.e. a power amplifier to raise the level of signals fed to the network analysers and special elements for taking off the voltage and current signals of the electronic generator station. The use of such elements is dictated by the need to reduce the computation errors due to the consumption of the measuring circuits connected to the network analysers. These errors are the lower the less is the proportion of current taken off for measuring the basic current of the circuit and the lower the power consumption of the shunts and series resistors. The power amplifier raises the level of the basic current and, consequently, reduces the first error component. Ingenious current take-off circuits used in the electronic generator stations

utilize the properties of the operational amplifiers and reduce the second component.

Today, there exist a number of machines operating on this principle. These include the "Delta" machine developed by the All-Union Institute for Power Engineering (VNIIE) and successfully used for more than 20 years, the СЭВМ machine of analogous design developed by the "Energosetproekt" research institute, an experimental machine developed by EAI of the United States, etc.

The most difficult part of the design process is the realization of direct converter I which generates harmonic oscillations controlled by the signals from the element for solution of the swing equation. The difficulties arise from the fact that accurate simulation of fast processes is required when investigating the transient, and particularly resultant, stability of the power systems. These processes are characterized by the high rate of frequency change of the generator being simulated (up to 20% per second) and its high deviation amplitude (up to 10%). By using the frequency ω_n in the network model (exceeding the frequency of the original system, ω_s) and the time scale slowed down M_t times, it is possible to reduce these factors K times, where

$$K = (\omega_m/\omega_s)\, M_t \tag{6.28}$$

But the possibility of increasing ω_m is limited by the requirements for a high Q-factor of network elements (in the network analysers used in Soviet practice the ratio ω_m/ω_s does not exceed 4-8). Simulation should be preferably done in real time or on a speeded-up time scale. For this reason, the rate and magnitude of frequency change at the output of the electronic generator station remain high and the ordinary approximate methods for controlling the frequency of an a.c. source applicable to radio engineering are impractical in this case. They are replaced by more accurate methods based on the use of the analog computing elements.

In this connection, two methods came under investigation, one of which was called the *method of angle addition* and the other, the *method of velocity addition.* According to the first method, a signal proportional to angle obtained at the output of the swing equation integrator is summed with a certain steadily rising quantity $\omega_s t$ (coordinate of a synchronously rotating axis), and then the resultant argument is subjected to functional conversion, producing an output signal of the form $\sin(\omega_s t + \delta)$.

The second method implies summation of the slip value relative to a synchronously rotating axis s (which is also produced by the swing equation integrator) with a certain constant ω_s (which is a derivative of the coordinate of a synchronously rotating axis).

Obviously, this gives

$$\int (\omega_s + S)\, dt = \omega_s t + \delta + C \qquad (6.29)$$

The difference between the two methods becomes apparent when we consider the question of limiting the range of variation of the signal coming for functional conversion. The function generators which effect this conversion may provide for the range of argument variation of $\pm\pi/2$; $\pm\pi$; $\pm 2\pi$ and so on but not for its infinite growth. For this reason, the value of the argument should be made cyclic, i.e. converted to a sawtooth, triangular or other form. It should be noted that the shorter the cycle of argument variation, the easier it is to obtain its function.

When using the first method, the argument is cycled by converting it into a sawtooth form. This is done separately for each component of the argument, so that $\omega_s t$ is cycled within $0\text{-}2\pi$, and δ, within $\pm 2\pi$. As a result, the function generator should provide for a range of argument variation of $0\text{-}6\pi$, and the sawtooth waveform of the signal applied to it should have a steep trailing edge which in ordinary function generators is expanded and turned into a spike distorting the output signal.

The second method is devoid of these disadvantages. In this approach, subject to cycling are not the separate components but the total argument which is converted into a voltage of triangular waveform with a signal variation range with an angle of $\pm\pi$, and this voltage is then easily converted into a sine wave. A disadvantage of this method is the drift of the integration constant C. Nevertheless, a comparison between the two methods from the standpoint of converter accuracy, complexity of design, etc. will be in favour of the second method, i.e. the method of velocity addition. Besides, the inherent disadvantage of this method can be overcome as described below.

A block diagram of direct converter *I* set up for velocity addition is shown in Fig. 6.27. From the inspection of the diagram which has been simplified for clarity, one can see that the setup consists essentially of two parts, i.e. a triangular wave generator (see Fig. 6.8) and an associated frequency control circuit which functions in accordance with expression (6.16). This approach is not inconsistent with (6.30) and only testifies to the fact that the instantaneous frequency is always a derivative of the phase angle. At the same time, it makes it possible to explain the operation of this circuit in a more representative manner.

Considering the closed loop formed by amplifier *A1* and associated components as a generator of periodic oscillations, we shall class these oscillations as self-sustained and take into account that, apart from the loop parameters, their frequency is affected by its operating

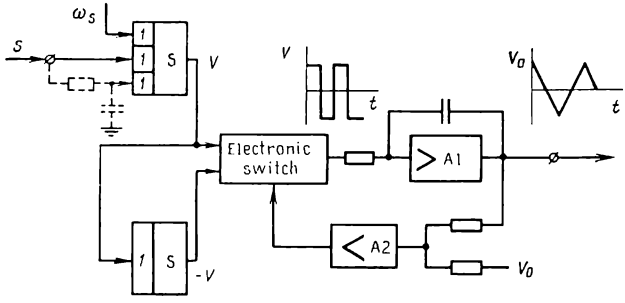


Fig. 6.27

conditions and particularly the drift of amplifiers *A1* and *A2*, etc. If we consider this generator as an isolated one, we should acknowledge that even under normal operating conditions the output frequencies of all electronic generator stations of the machine will differ from one another, a condition which is not observed in the original.

To clear away this difficulty, a network shown in broken lines in Fig. 6.27 is incorporated in the generator operating under normal conditions. The network acts as an astatic frequency control element to nullify the drift. In addition to this network, another network is connected to the electronic generator station under normal conditions to increase the damping coefficient [quantity K_s in expression (6.26)]. These measures permit stabilization of the electronic generator station and the operating conditions of the system simulated with their help. When simulating system disturbance, all types of additional stabilization are automatically removed but this is not important due to the transient nature of this condition.

The triangular-wave oscillations generated in this manner are subject to further conversion. In a simplified generator station, this conversion is completed in the sine function generator, with the amplitude of its output voltage E' adjusted manually by the operator when reproducing the specified condition.

In the case of the complete generator station, a cosinusoid is required in addition to the sinusoid, and both are multiplied by the corresponding components E'_d and E'_q of generator e.m.f. and added to form a sum signal E'. Thus, when setting the operating conditions, the operator should manipulate the setter in the model of the removed voltage regulator. The conversions are completed in the power amplifier which directs the signals to the network model.

The reverse conversion begins by discriminating the current signals in the circuit of the electronic generator station. It is impracticable to insert ordinary shunts or current transformers in this circuit since

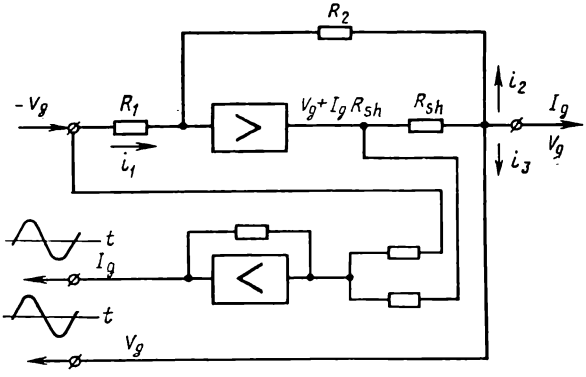


Fig. 6.28

this would result in power tapping and distortion of the results of computation. Therefore, use should be made of the properties of the operational amplifier by connecting appropriate element R_{sh} into its feedback loop. This arrangement is shown in Fig. 6.28. Note that the value of current i_2 is negligible as compared to I_g. The value of I_g is also practically unaffected by current i_3 taken off by the circuit for measuring the terminal voltage of the generator station. Given the values of current and voltage vectors, it is possible to obtain signals indicating the effect of a particular generator station on the operation of the system. These signals perform the function of feedback in the electronic generator stations.

In a complete generator station, these signals are used to represent the power and projections of the current vector on the rotor axis of the given electronic generator station, designated in the diagram as I_d and I_q. A simplified generator station requires only the signal representing power, but it can be replaced by the active current component which is essentially a projection of one vector on the other (the vector of current I_g on the e.m.f. vector E_g).

To take power measurements by means of an analog computer, it will suffice to multiply the instantaneous values of current by the voltage and then to filter out the constant component from the resultant signal (the presence of a variable component in a power-dependent signal is not typical of the normal operating conditions of a power system; it should be borne in mind, however, that the network model is a single-phase system). The projections of one vector on the other in the electronic generator station are measured by phase-sensitive networks provided for the purpose.

Just as the signals coming from the power transducer, the signals coming from the phase-sensitive networks undergo filtration which consists in smoothing the signals fed from rectifiers or special swit-

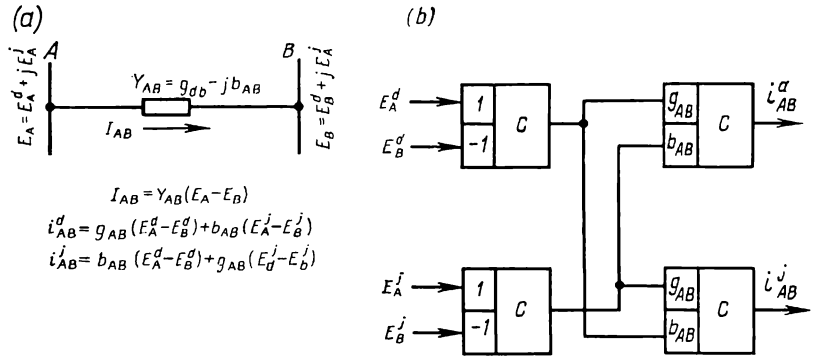


Fig. 6.29

ches. The smoothing action distorts somewhat the dynamic characteristics of the stations but the amount of distortion is fairly insignificant for all practical purposes.

The performance of the setup shown in Fig. 6.27 was tested by Soviet engineers on several existing installations based on the network analyser with a rated frequency of 196 Hz. These installations comprise from 4 to 16 generator stations of various types. For the most part, loads are simulated by permanent shunts and load models corresponding to the static characteristics or performance equations of induction motors are connected at some critical points. Work is currently under way for integration of the simulation facilities with digital computers to permit automation of the process of determination of stability regions, adjustment of the stability control schemes, etc.

The results of computations performed in real time have been repeatedly compared with the results of slower computations peformed by digital computers. The comparative analysis has shown that even when using relatively low-quality amplifiers the difference in the end results, i.e. in the value of the transient or resultant stability, does not exceed several per cent. A machine under development by EAI (USA) is based on the network model with a working frequency of 5 kHz and intended for computation on a time scale speeded up 100 times.

A third type of special-purpose machines has been developed by Westinghouse for the New England Power Exchange, NEPEX (North-Eastern United States). In its present form, the machine is primarily intended for evaluation of different variants of load flow in the system in the event of disconnection of power lines and generators. The machine comprises line and bus elements each of which

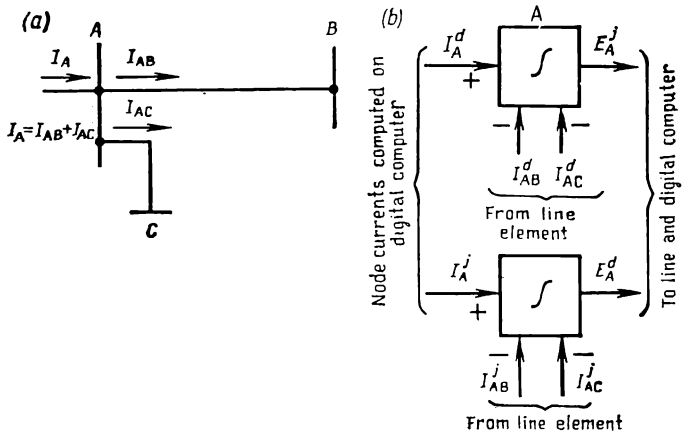


Fig. 6.30

consists of two parts executing prescribed operations in two axes, i.e. real and apparent.

The operating principle of a line element (Fig. 6.29*a*) consists in determining the current in the line for the specified voltages. For this purpose, use is made of four operational amplifiers and four resistors per node (Fig. 6.29*b*). It is assumed that the resistors are so selected as to obtain transfer coefficients specified in the drawing and corresponding to the admittance characteristics of the power line being simulated.

The element which serves for measurement at node *A* (Fig. 6.30*a*) is controlled from a digital computer (Fig. 6.30*b*). In this way, the analog and digital methods of data processing are combined. In the given case, the process involves selection of resistors simulating the load separately in the active and reactive parts of the element. The resistors are selected so as to satisfy the equation expressing the functional relationship between the load current and voltage at the node (e.g. the condition of constancy of load power, etc.).

Tests conducted on the machine in question directly within a power system consisting of 273 lines in 345, 230 and 115 kV networks have shown that it takes as little as 14 min to compute 33 possible operating conditions with the aid of a small digital control computer of the P-2 500 type.

REVIEW QUESTIONS

1. What is meant by the analog form of information representation? Can analog information be represented in a floating-point form?
2. What is the difference between analog and digital computers? Does it lie only in the form of information representation?

3. What are the properties of the sequential and parallel structures in relation to the changing scope of problems?
4. Write down the basic equation of the modern operational amplifier. Why are the amplifiers of this type extensively used in present-day analog computers?
5. Draw schematic diagrams of operational amplifiers used to reproduce the summation, integration and differentiation operators. Is it possible to use one operational amplifier to reproduce several different operators?
6. How are nonlinear functions reproduced in analog and digital computers? Which method is faster?
7. Describe the structure of a hybrid computing system. How do the analog and digital subsystems interact within a hybrid computing system?
8. What part do the components of a hybrid computing system take in solving a problem?
9. Define the operating principle of special-purpose computers for economy dispatch What equations are solved by these computers?
10. Define the operating principle of special-purpose computers for evaluation of electromechanical transient processes. What equations are solved by these computers?

Chapter 7

Use of Digital Computers in Dispatch Control of Power Systems

7.1. General

One of the basic tools of power system dispatch control of today is the digital computer. Digital computer applications in the field of dispatch control have their specific paspects, particularly as regards information processing, and it is this problem that the present Chapter is devoted to.

The first digital computers, processing data according to how it is preprogrammed, appeared some three decades ago. Since then, digital computers, both as science and technology, have come a long way, and as many as three generations of them have materialized.

The first-generation digital computers had thermionic hardware, and used magnetic drums as a storage element.

The second generation of digital computers had semiconductor logic, a ferrite core working memory.

The second-generation computers were much faster, and proved successful not merely in business-oriented computations, but also in solving large-scope scientific and technical problems and in direct automatic control applications. Interestingly enough, these computers had similar structure and shared a common operating principle, although substantially divergent capabilities were often required of them to suit specific applications.

Thus, the computers intended to handle finance, accounting and other business-related jobs (hence the names "business" and "business-oriented" machines) were required to process large amounts of input and output information and have a high-capacity memory for storing that information, but need not necessarily be very fast. On the other hand, a high speed of computations becomes of a paramount importance in computer-aided solution of scientific and engineering problems, while the volume of information put in and brought out of the computer can be quite moderate. Finally, the computers for automatic control must combine high speed with a large-volume input/output (I/O) capability, but can well do with a medium-capacity ferrite core memory.

By similar account, the optimal computer word length (size) can also be said to be application-dependent. Thus, the machine words in "scientific" computers must be longest of all (between 45 and 60 binary digits, or bits), while for machines employed for planning and business computations a word length of 32 bits is adequate. In automatic control computers, the word size constitutes 24 bits at the most, and is typically much shorter than that.

The capabilities of the second-generation digital computers were too limited to have such vastly varying requirements realized in a single installation. Therefore originally the trend was towards building highly specialized machines conceived, designed and adapted for use in a given operation environment. And, although each such machine did retain the ability of solving virtually any problem from another area, it could do it much less effectively.

In the Soviet Union, manufactured as business-oriented were computers of the Minsk type, certain computers of the Ural family, etc. Other computers, such as the M-220, M-222, БЭСМ-4, БЭСМ-6 and others, were adapted for solving complex scientific and engineering problems, while the Dniepr-1, ВНИИЭМ-3, УМ-1НХ and some other special-purpose installations were designed specifically for automatic control uses.

The experience gained in the use of these machines did much in the way of their perfection and development. This is especially true of automatic-control computers, with which new concepts and options were first developed and later materialized in third-generation computers. Among these concepts and options are, for instance, the external interrupt capability enabling software branching from one program (routine) to another, organization of storage protection and, most importantly, a new approach to configuring computer installations.

Computerized control systems designed for special-purpose uses had their hardware configuration rigidly fixed and strictly individual. It therefore turned out to be impossible to employ, in all conceivable situations, one and the same assortment of technical facilities that come under the term "digital computer", and manufacture had to be launched of a whole range of computer devices of various purposes, capabilities and capacity. Based on a common concept, these devices lended themselves easily for transformation into computer systems capable of meeting specific consumer requirements.

The term "computer system" (rather than simply "computer") that came into use then was naturally carried over onto third-generation computer technology.

The first practically implemented third-generation computer system is generally agreed to be the IBM System/360, announced in April, 1964. This system, which cost some five billion dollars to develop and build, had a profound effect on the advancement of

computer science and technology in all industrially developed countries of the globe, the USSR being no exclusion. In fact, the IBM System/360 became the prototype of most of the large computer installations later built in other countries.

Realization of the IBM System/360 concept was made possible due to the introduction of highly integrated microelectronic hardware, with which computer systems became much faster, more compact and yet much more reliable. Another important by-product of the new concept was a successful solution of some of the more general problems related to improved computer efficiency.

To begin with, segregation of digital computers into various categories according to their uses and capacity was assumed no longer practical. This opened the way to building all computers of a given model (class) and application on a common basis, with their programs fully compatible (which means that programs compiled for installations of one class and capacity could be used with equal success to solve similar problems on installations of a different class and capacity). Such an approach has dictated that the computer proper be sectionalized into several individual devices, for example the central processing unit (or processor), the main memory (or storage), peripheral units, etc. Further, several models of each of these devices (that shared a common logic structure and differed only in their capacity) could now be made available. As a result, appreciable improvements became possible in the economic efficiency of computerized systems designed not only for automatic control of technological processes, but also for automated control and management of industries and solution of scientific and engineering problems. In each of these fields of applications, it became possible to configure the structure and composition of the computer systems in a way best suited for a given class of jobs.

Production of computer hardware was made simpler to organize, because individual manufacturers could now specialize only in the production of certain devices. It is along these lines that the CMEA United System of Electronic Computers (ES EVM) was conceived and implemented. The computers of this system are designed and produced jointly by the CMEA member nations, each of which supplies only certain components of that system. A range of computer models (such as the EC-10, EC-20, EC-30, etc.) is now available to meet various consumer demands. The least capacity models were nicknamed "junior", while the more powerful ones became commonly called "senior".

Each type of the ES EVM devices is assigned a unique designation code (for example, 20 for central processing units, 30 for ferrite core memories, etc.). To obtain a complete code combination of a specific device, the code of the model in question must be added to its

type code. For instance, EC-2020 denotes a Model 20 central processing unit, EC-3030 is a Model 30 memory, etc. In this way, both the device function and its capacity class can easily be determined. Besides, the last digit of the model code can be used to indicate the device modification, while that of the type code can serve to indicate certain optional information. The codes beginning with the number 10 denote a certain minimum assortment of devices that make up a complete digital computer (for example, EC-1010 is a Model 10 computer).

All parts of the ES EVM system are directly compatible through standard interfaces to ensure a unified linkage structure and parts interchangeability.

Since the IBM System/360 and similar computer systems had come into use, it became clear that one of the primary goals which their authors sought to attain (and that was to have all conceivable computer applications served with a single range of devices) was never fully implemented. Therefore, the IBM engineers had to combine their system with some extra processor models developed specifically for execution of certain functions and options. Yet, creation of the new system was a big step forward towards attaining that goal, which was later to become a fundamental issue in computer technology.

Designers of third-generation computer systems faced, however, another, and no less complex, problem. Indeed, technological progress highly improved system parts directly responsible for data processing, while having little or no effect on the data input-output devices. Ways had therefore to be found for using the new parts efficiently in an environment where the speed of data insertion and retrieval was clearly inadequate.

True, for some scientific, engineering and technological applications this was a minor problem. Thus, in the computer-aided research of sufficiently persistent transients in complex dynamic systems the time required to put in the necessary data, even if the processor is quite fast, will be considerably shorter than the time spent on actual processing of that data. Such situations, however, are fairly rare. More often than not, the data input into third-generation computer systems is processed so fast that the costly electronic hardware will be idling most of the time if no special measures are taken to avoid it. One way to do so is to have the data put in and brought out in several parallel flows directly accessible to the system main memory without undue participation of the central processing unit.

General organization of a third-generation computer system logic is shown in the block diagram of Fig. 7.1, which depicts numerous input/output devices (I/O devices) linked with other special devices known as channels. The latter serve to ensure data interchange with the main memory on a par and concurrently with the central proces-

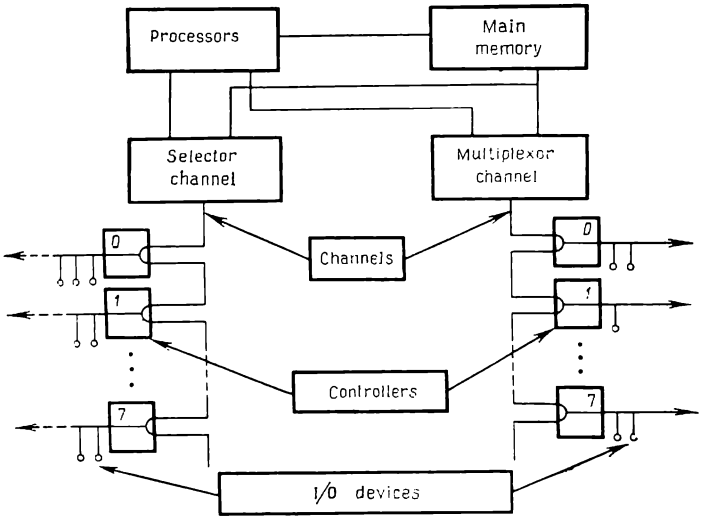


Fig. 7.1

sing unit (processor). Note also that the data being exchanged is standardly organized into whole blocks, which means that once the data exchange mode is set (i.e., the I/O device number, magnetic-core memory origin and data block size are all specified), the central processing unit can temporarily terminate execution of a current program and jump to another program for which the data are available.

This mode of operation, known as *multiprogramming*, impresses two important features upon third-generation computers systems.

Firstly, it implies the use of highly developed control facilities, which must necessarily be automatic. The problems arising in this regard are formidable, for not only the operation of a large number of concurrently operating devices has to be properly orchestrated, but their work load must also be distributed carefully in order that all the system resources and capabilities were fully utilized. Therefore unlike the second-generation computers, computer systems of the third generation rely less and less on hardware control and become almost totally program-controlled.

Thus, in addition to the standard input/output, print out and such like programs organic to the digital computers of the second generation, the third-generation computer systems have available to them a whole system of software which has no direct bearing on problem solution but is responsible for the executive functions of controlling and organizing the operation of the parent system. This system of software has become known as the *operating system*.

Secondly, multiprogramming can be organized in more than one way. The simplest option is what is known as *batch processing*, whereby the tasks to be solved by the system over a given stretch of time are batched into a single set and are then treated as the system's scheduled load for that period of time. The information needed to execute the batch tasks (i.e., the program and raw data) is distributed among appropriate devices, after which further operation (identification of tasks and their solution) is automatic.

Batch processing offers much in the way of optimal utilization of the system resources, especially if the tasks are properly batched (it is considered good practice to always have scientific and engineering tasks that normally require little information exchange with external devices batched together with business-oriented jobs with which the information exchange is intensive). Batch processing is inconvenient, however, for the computer users in that they are denied control over execution of their respective tasks for as long as the current batch is being executed. This prompted designers to equip most of the third-generation computer systems with a different mode of multiprogramming known as *time sharing*.

Like batch processing, time sharing implies multiple jumps from one task to another. These jumps, however, are no longer conditioned by the need to interchange information with external devices, but are rather carried out on a regular basis and quite frequently, normally once every 10 to 40 milliseconds. True, the time-sharing mode makes the system operation much more difficult to control, but it also makes the central processing unit impossible to be "monopolized", i.e. occupy it for an appreciable length of time with a job that requires little information exchange with external devices (examples of such jobs were given earlier) at the expense of other jobs whose execution requires an intensive exchange. Besides, time sharing permits interleaving of problem solution with a dialog with the external environment—a feature also beneficial from the standpoint of computer efficiency.

The term *dialog* here implies such an approach to the solution of problems whereby the decision to move on to the next job is made dependent on the results of the preceding steps. In broad terms, any automation external to the computer system can be looked upon as a party to that dialog, but in most cases the computer converses with man—a programmer, operator, engineer, researcher, or another human "task giver".

In time-shared computer systems, the I/O devices often take the form of special consoles that have come to be called *terminals*. These terminals allow the user to prepare, for input into the system, a segment of information (program and data) needed to solve a certain (fairly small mostly) phase of a given problem (a part of the relevant information may already be in the system storage).

The terminals are queuing to be connected to the computer system, when the latter can accept the user-prepared information, process it (immediately if possible), and send back an appropriate response for the user to assess it before authorizing a move to the next phase.

With appropriate communication links (and the use of space communications is not infrequent for the purpose in recent years), the terminals can be sited as far away from the computer system as necessary. Under such conditions, time-shared computer systems proved to be very convenient, for they can provide computer services to a large number of users, giving each of them access to a certain amount of computer time backed up by the entire system resources. Of course, the new time-shared computer systems, unlike conventional computation centers of the past, must be permanently linked with their users, and be ready to serve them at any time. It is to stress this latter feature that the newer systems have acquired the name *on-line* as distinct from the older *off-line* computers.

An off-spring of the on-line concept are the so-called executive systems, which already have all the necessary programs stored internally and need only to be fed with source information (raw data) along with a request to process it. At first glance these systems would seem to be no different from the familiar on-line systems adapted to handle a specific range of jobs. This, however, is not quite so. Despite the broadly divergent functions (such as inquiry services, automatic control command generation, recording of information for its subsequent display, etc.), all executive systems share one essential feature in common—no matter when a request is submitted, the system must serve it within a limited space of time, for otherwise the computer-generated response becomes meaningless or useless.

The on-line systems meeting this requirement are called *real-time systems*. The latter term is, in fact, synonymous to the terms BMCS, APPMCS and ADCS, and reflects the inherent properties of such systems well enough. Indeed, the pace of their operation is conditioned entirely by the rate of occurrence of external events, with regard to which the system can neither be running ahead nor lagging behind, with the result that the time factor for them becomes an objective reality.

Simpler real-time systems serve all their information sources and recepients by executing a chain (sequence) of appropriate programs on a cyclic basis, with the external stimulus initiating each execution cycle normally provided by a special real-time clock signal. In the simplest systems, the cycle duration is long enough to have all operations likely to be initiated by the preceding signal fully completed by the time the next signal comes in.

These systems left much to be desired in terms of efficiency, and it was soon found that it is much more practical to make the system

waiting for an appropriate request before servicing a particular source of information or user. The system however, must then be able to automatically recognize which of the incoming requests has top priority and then move from one program to another strictly on the request priority basis. This, in turn, means a more complex control over the system operation and, consequently, higher software and hardware costs to support it.

Real-time computer systems are also more costly because they must necessarily meet higher reliability standards. A high reliability can hardly be ensured except by making the system structurally redundant, for example by employing some standby equipment which can always take over from the main one if necessary. If no such contingencies arise, the standby equipment can be diverted to tackle certain auxiliary tasks. As a result, the eventual cost of the system turns out to be fairly high, and therefore careful engineering and utilization are essential in their success.

It can thus be concluded that information processing has become a branch of industry of its own standing which, like other branches in which sophisticated and complex equipment and technology is employed, strives not only towards a higher productivity, but equally towards a better efficiency. This necessitates the use of advanced methods, techniques and approaches, including automatic planning and monitoring of the system functioning.

In dispatch control of power systems, modern information (data) processing is used on a large scale. A specialist working in this field must therefore keep abreast with the latest developments and new concepts and ideals, and it is to aid him in this that the present Chapter is called upon.

7.2. Information: Its Formats, Input, Output and Storage

The comparison of information (data) processing to other branches of industry is, of course, only partially true. Whereas in industry the information-and-management process merely proceeds along the manufacturing process proper without ever crossing, let alone blending with it, in information processing devices these two processes share a common physical nature and can well cross each other or even fuse. Yet, two kinds of information can always be identified in computer systems—the information (data) to be processed, and the information on how to process it. Applied to the former are such names as source information, raw data, numeric data, numbers and operands. The latter kind of information includes programs (commands, instructions, orders, directives), attributes (labels, subscripts, designators) and signals (masks, flags).

As things stand today, information of either kind, prior to its

input into and after its retrieval from a computer, takes the form of symbols denoting numerals, letters and various other characters, and is therefore referred to as *alphabetic-numeric* or *alphanumeric* (*alphameric*). On the other hand, computers can understand nothing but codes of these symbols, normally in a binary and positional format.

A binary code is one in which each individual element can assume two states (values) only, for example a 1 and a 0. These elements are known as *binary digits*, or *bits*, although the former term is, strictly speaking, applicable only to binary number codes.

A code is called *positional* if the value of each of its elements is conditioned by the position it occupies with regard to the surrounding elements of the same code combination or the boundaries of that combination. If the element position is time oriented, the code is called *serial*. Otherwise, the code is referred to as *parallel*.

Codes and formats. As a unit of information, a bit is very small, for it can only represent one out of two unique states (values) of a set of two symbols or a two-character alphabet. Therefore larger units of information are more convenient to use in computers. Hence, the IBM System/360 and similar computer systems operate with 8-bit code combinations, or *bytes*.

A byte became the universely adopted unit of information not merely because it allows two digits of a decimal number to be densely "packed" (with four binary digits per each decimal one), but also because its size is close to the requisite symbol code length. In the earlier days of computers, seven binary digits were required to represent each single symbol (examples are the ACSII and KOI-7 information interchange codes). With the introduction of a byte-oriented information structure, it was found more expedient to extend the codes to include eight bits, as was done in the EBCDIC and DKOI codes in which one byte can represent one out of as many as 256 unique values.

The use of bytes necessitated the need to modify the internal arithmetics of computers. Most machine instructions, as is known, include an operation field and an operand field filled with numbers. But, whereas in the computer these numbers are binary, in source programs they are octal. Under these conditions, six machine digits correspond to two program digits, which is hardly convenient with an 8-bit byte. For this reason, a change was made for a hexadecimal number system, with the six symbols needed to represent numerals replaced by the first six Latin letters. Hence, one digit of an operation or operand address code could now assume the following values: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, or F.

For the purposes of data storage and transfer verification, a ninth (check) bit is internally added to each byte, although this is never programmer-written or accounted for in source programs.

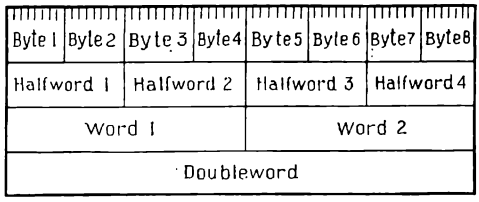


Fig. 7.2

In some cases, a byte is defined as a 6-bit combination of a 64-character alphabet. Besides, to denote fixed-length code combinations, use is sometimes made of the terms "symbol" and "word". Their length, however, is not standardized and has to be verified in each combination.

If still larger units of information are required, the word byte is prefixed with the letters K and M, so that 1K byte $= 2^{10} = 1\ 024$ bytes, and 1M byte $= 2^{20} = 1\ 048\ 576$ bytes.

With a byte used as a basic unit, a flexible information structure (Fig. 7.2) can be accepted, whereby two bytes make up a halfword, four bytes—a fullword (or simply word), and eight bytes—a doubleword. It also permits the use of variable-length operands (halfwords and words with fixed-point numbers and doublewords with floating-point numbers), as well as instructions of various formats from two to six bytes long.

Input and storage. To be computer-readable, all data must first be transferred to a *storage* of some form, i.e. a material or medium alterable during recording in such a way that when accessed it would respond with a string of pulses in strict correspondence with the code combinations recorded.

All data-carrying media external to a computer can be classed into *machine documents*, on which the data are stored in a form perceptible to man and machine alike, and *secondary storage*, on which the stored data are no longer perceptible to man and therefore require special facilities to be accessed and read.

The secondary storages can provide data exchange at speeds that are two to four orders of magnitude as high as those of the machine documents units, although the computer's internal storage (memory), which normally takes the form of random-access memories, is still faster. Besides, third-generation computers are often equipped with numerous bulk memory (mass storage) devices operating at various speeds.

As of today, most widely used machine documents are paper, cardboard and plastic cards and tapes, on which the necessary data are punched so that each code combination and each code digit is

allocated a unique punching position. A hole punched denotes a 1, while an unpunched position denotes a 0.

The process of punching, also referred to as *machine documents (or input) preparation*, involves the use of special equipment, such as an electrical typewriter (doubling up as an encoder) with a punch adjunct. Striking one of the typewriter's keys makes the respective character (symbol) to be typed on a paper roll, and at the same time sends to the punch a string of electrical pulses corresponding to that character's code. The punch responds to these by punching holes at appropriate punching positions of the card (tape) and advances it one position further. The thus prepared data can next be verified (or "proved") and then read into the machine, either optically or electromechanically.

Punched cards are considered to be one of the most convenient forms of machine documents, for they allow any segment of the stored data to be fairly easily manipulated, altered or modified. Punched tapes offer less in this regard, and are therefore used as auxiliary documents, primarily with terminal equipment.

On the other hand, reading of data from punched cards (or rather feeding these cards for the data to be read) is an intricate and slow process, the attainable speeds being in the range of between 0.5 and 0.8K bytes per second, which is clearly inadequate in today's environment. For this reason, all data entered into third-generation machines from punched cards is transferred to some secondary storage before a program execution can be initiated. The functions of the secondary storage are usually performed by magnetic disk, drum and/or tape storage units. A wide range of these devices is, for example, available with computers of the ES EVM family.

As their name implies, magnetic storages rely on the principle of magnetic recording to store machine data, with the result that the latter become imperceptible to man without the use of special facilities. This drawback, however, is more than made up for by the high read/write speeds attainable with these units and their multiple-access capability.

Secondary storages are commonly classed into two major types: *sequential-access storages* where a given data array has to be scanned sequentially before the requisite fragment of it is located, and *direct-access* (or *random-access*) *storages*, where no previous sorting of data is necessary. Magnetic tape storage units belong to the former type, while magnetic drum and disk storages are referred to the latter type of devices.

Modern magnetic tape storage (MTS) units have the data stored on 12.7-mm wide tapes transported at speeds of 1.5 to 4 meters per second. The recording (writing) density is 32 or 63 pulses per millimeter, with the data being read or written in variable-length segments, each accommodating as many as 18K bytes. The data transfer rate

is one the order of 48 to 240K bytes per second, with one tape reel capable of holding up to 20M bytes of data. All this turns magnetic tapes into a high-capacity and fast data storage medium whose only serious limitation is the sequential nature of access.

Among the various secondary direct-access storages, magnetic drum units are perhaps the simplest. In the ES EVM computers, two models of these devices are available, with a capacity of 2 and 6 M bytes and a data transfer rate of 0.8 and 1.25 M bytes per second, respectively. The data access time (also called drum latency time) averages half the drum revolution time, and constitutes some 20 ms at a drum speed of 1 500 r.p.m. On the negative side, magnetic drums are bulky, critical in use, and utilize the data-carrying medium inefficiently, because data are only recorded on the drum's outer surface.

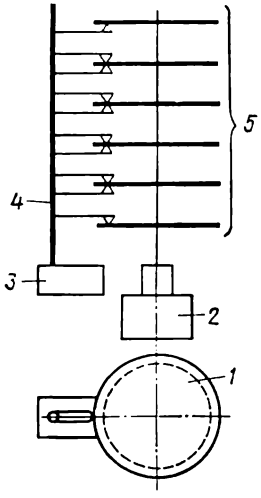


Fig. 7.3

Magnetic disk storages (MDS) are devoid of most of these limitations, and outperform all other types of secondary storage in many respects. A magnetic disk storage unit is a device in which data are recorded on the magnetic surfaces of a thin rotating disk. The method used to record data is akin to that used on grammophone records, except that the tracks are concentric rather than spiral. Yet, the data-carrying medium is fully utilized, and a magnetic disk measuring 350 mm in diameter can accommodate as many as 200 or more data recording tracks.

Two kinds of magnetic disk units are currently in use: those with removable (exchangeable) disk packs and moving access arms, and those with non-removable disk packs and fixed access arms.

A sketch of a removable-pack, moving-arm MDS unit appears in Fig. 7.3. The storage unit consists of drive motor *1* with spindle *2*, head-positioning motor of the disk drive *3*, a set of read/write heads on moving arm *4*, and a pack of disks *5* capable of storing some 72M bytes of data at read/write speeds of more than 150M bytes per second. There is also a spare disk pack in a protective sheath that is easily removed once the pack is installed in the drive.

Removable-pack magnetic disk storage units offer two major advantages—a practically unlimited capacity and a disk pack interchangeability. The data access time, however, is restricted by the revolving action of the disks and the arms movement. Since the heads have to be positioned over a specific track, the average access time (search

time plus rotational delay) ranges from 50 to 100 ms, depending on the device type and the head drive motor used.

In search of the requisite data, all heads of such a unit move in unison, and therefore an "information cylinder" rather than a "track" is said to be accessed. An information cylinder is thus an imaginary cylinder formed by all the tracks located one beneath the other on the disk surfaces throughout the pack.

In contrast to the removable-pack MDS's, the capacity of permanent (fixed-head) pack units is limited, although it is still fairly high in most cases (100M bytes or more). Besides, no head movement is necessary in these units, for a head is provided per each disk track. As a result, the data access time is conditioned entirely by the disk rotational speed. One example is provided by the Burroughs corporation of the United States, which markets magnetic disks with a capacity of 150M bytes and an average access time of 5 ms. This means that over a period of merely 5 ms it is possible to locate the necessary number in a library of 32 volumes of 200 pages each.

Magnetic disk units are one of the most important ingredients of third-generation computer systems, which could hardly at all be made operational without them. Magnetic disk storages operate on-line with random-access memory units and other kinds of computer storage. In fact, there are now systems in which, despite the vastly different physical nature of RAM's and MDS's, both are numbered throughout to form what is called the virtual, or mathematical, storage.

Random-access main memory units are generally considered to be the bottleneck of third-generation computer systems. Since their capacity is required to be quite high (128, 256, 512 K bytes and more), acceptable per-byte storage costs can so far be obtained only through the use of magnetic-core devices, whose speed has not improved noticeably since the era of second-generation computers, and is still in the range of 1 μs per one "erase/write" or "read/refresh" cycle.

To counter the apparent "slowliness" of magnetic core memories, resort has to be had in higher-level models of current-generation computers to wide-access techniques, with 2, 4 or 8 bytes of data accessed during a single cycle. Therefore the access width is just as important a characteristic of magnetic core memories as their cycle duration.

Output. In conventional computer centers employing third-generation off-line computers, data are normally output to alphanumeric printers of the "line-a-time" type capable of printing at speeds of 1.5 to 2.5K bytes per second in lines of 128 characters. These are mostly the type-wheel printers with electromagnetically driven printing hammers, allowing the print type to be easily changed from, say, Latin to Cyrilics.

A prominent role in data output is also played by devices providing a direct operator-to-computer interface (an example are electrical typewriters). These devices ensure a conversational mode capability, with the data put in and brought out of the computer at a rate of up to 10 characters per second. Besides, data are also output (especially for the purposes of filing and subsequent exchange) onto punched cards and tapes.

A large group of data output devices widely used in control system applications was described in detail in Chapter 3.

7.3. Data Processing. Central Processing Unit

The concept of data processing can be approached in two ways. In most general terms, it can be said to encompass the entire process of entering data into a computer system, its storage, transformation (or conversion) and output to the user. This approach is very important in that it underscores the fact that a correct choice and proper functioning of all and every of its elements are vital to a successful execution of a computer system functions.

On the other hand, if we consider a computer system in somewhat greater detail we can notice that its largest part serves primarily to transfer, interchange and store data, while the data processing functions proper are entrusted to only one of its parts known as the central processing unit, or central processor.

Now, *a central processing unit* (CPU) can be defined as that part of a computer system (see Fig. 7.1) which performs a dual function: (a) it accepts data from the main memory, converts them with the aid of arithmetic and logical operators and passes the results back into the main memory, and (b) it controls the above process and organizes the operating of the entire system.

This apparent duality of the CPU functions is due only to the fundamentally similar physical nature of the technological and information management processes typical of data processing, and is not at all mandatory. More than that, two separate entities can usually be identified within the central processor itself: an arithmetic and logic unit (ALU) which performs the former function, and a control unit (CU) responsible for the latter function. Yet, combining the ALU and CU in a single device is a carry-over tradition from the early days of computers, and one which is almost never departed from. Note also that this is not so with the main memory, the recent tendency being to treat it as a separate entity, although in some computers the main memory is still made part of the central processing unit.

The following discussion will focus upon general architecture and basic features of individual units and devices of third-generation central processors, their relationship with the main memory and

attainable data processing speeds, formats of the CPU instructions, and the methods used to interchange data with peripheral devices.

Arithmetic and logic units. In data processing, these play a key role by performing preprogrammed arithmetic and logic operations of data.

The term "arithmetic and logic unit" has become firmly associated with third-generation systems (as distinct from the older "arithmetic unit" concept applied to computers of earlier generations), not merely because it is more concise but also because it stresses the vital importance of logical operations in data processing. Besides, the new units have at least two extra features that set them apart from the older devices. These are the binary-coded-decimal (BCD) arithmetics and combinational logic.

As applied to an arithmetic and logic unit, the term *BCD arithmetics* can be defined as performing arithmetic operations directly on binary-coded-decimal numbers, without converting them into the binary format. This has become necessary because, as was already pointed out, modern general-purpose computer systems often have to handle business-related jobs which normally require fairly little computations. Under such conditions, the usual practice of having the numbers converted from decimal to binary prior to processing was found to be hardly worthwhile, and many third-generation ALU's have therefore been equipped with a special section specifically designed to perform relatively simple arithmetic operations on decimal numbers represented by their binary codes, without converting these numbers into the binary format. This CPU section, however, is very specific, and is beyond the scope of our discussion.

The second feature of modern arithmetic and logic units—the use of combinational logic—is essentially a projection of the fundamental ideas of computer electronics upon the use of logic algebra to perform arithmetic operations, which is indeed possible if the numbers are expressed in the binary system and the assortment of logical operations includes the store and delay operations. At the earlier stages of computer development, this possibility was mainly realized through the use of adders built around complement (T, or toggle) flip-flops which both added numbers and stored results. The advent of integrated microelectronics has made this approach impractical, and the flip-flops were left only with the function of storing the results, the operation of adding being accomplished by gating the logic signals through appropriate combinational logic circuits.

A combinational logic circuit (Fig. 7.4) is a circuit composed of AND, OR and NO gates arranged so that when a certain combination of logic signals, Y, is applied to its input, it would respond with an output combination, C, in full agreement with the circuit truth table.

When used in the capacity of a binary adder, a combinational logic circuit incorporates an appropriate number of columns (bits) each of which is characterized by an addend, A, and an augend, B. The operation of arithmetic addition in one column then corresponds to a truth table of the following form

A	B	C	Carry
0	0	0	0
1	0	1	0
0	1	1	0
1	1	0	1

In the circuit of Fig 7.4, the solid lines correspond to the above table. Signals A and B arrive to the circuit from the augend- and addend-storing flip-flops, while the sum and carry signals are gated to the output through switches K, $K1$ and $K2$ closed by signal Y generated in the control unit.

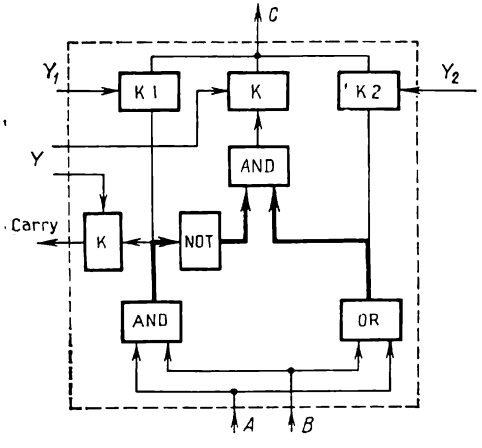


Fig. 7.4

The thin lines in Fig. 7.4 indicate that the circuit functions can be expanded. Specifically, if signal Y_1 or Y_2 is fed in from the control unit instead of signal Y, the circuit output will be a logic (rather than arithmetic) sum or product of the input values. With only minor modifications, the same circuit could be made to put out an arithmetic difference of the same values.

Similar circuits can be used as building blocks of multiple-column combinational adders with carry loops. Incidentally, it is the latter loops that condition the speed of every particular adder, since all other basic operations in an adder are completed almost immediately after the input has been applied. The capabilities of the basic circuit can be enhanced further by supplementing it with multi-column switches (gates) and input and output shift registers. Input registers are capable of shifting their contents a certain number of bits to the left or to the right. The output register is often equipped with the ability to analyze the contents of its most significant bit (or a special register overflow bit), and put out a corresponding identifier signal.

The net result, then, is a simplest third-generation ALU structure, shown in Fig. 7.5 with solid lines as containing a combinational adder (CA) and other elements*.

In combination with a main storage of an unlimited capacity, such an ALU permits realization of virtually any algorithm of preprogrammed data processing in which data are represented by binary codes. As an illustration to that, consider a more complex and yet in many respects important operation of binary multiplication. With binary numbers, this can be accomplished in a number of elementary add and shift steps, for example

1111	1111
1001	1001
1111	1111
1111	1111
10000111	10000111

The algorithm realizing one of these examples (the one on the right) is flowcharted in Fig. 7.6, where the symbol : = denotes the assign operation, i.e. gating of the relevant value to an appropriate main memory location.

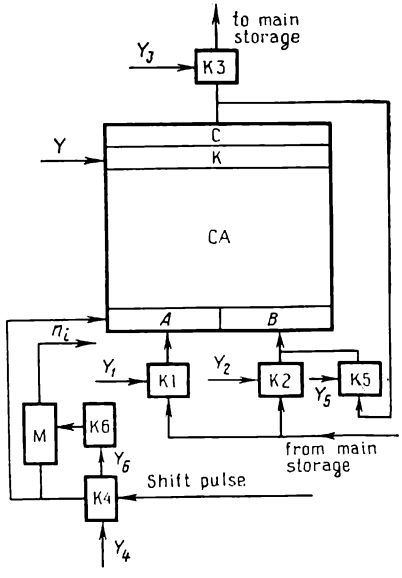


Fig. 7.5

Note that apart from the multiplicand A and multiplier B, the main memory also stores the number 0000 needed to transfer the code it stores into the output register (in order to analyze the contents of its most-significant bit), plus the number 0001 used as an end-of-operation delimiter. The product is also stored in a main memory location.

As is readily apparent, realization of the algorithm requires no elementary operations other than those a simplest ALU can accomplish (addition, shift and conditional carry). These operations, however, are fairly many, and execution of each involves access to the main memory for an instruction (or even an operand) fetch. This is obviously time-consuming, and means an inefficient utilization of available main memory space. As a way out, the simplest ALU structure can be augmented by certain options expanding its capab-

* The designation, purpose and operation of these elements will be discussed later in the text.

ilities. One of such options is considered below, with a multiplication operation providing the necessary example.

Consider again the ALU operation shown with solid lines in Fig. 7.5. The circuit options include the additional shift register, M; transmission gate $K6$; a device designed to output the identifier of the contents of the most-significant bit, n_i; and a link between the adder output and input via switch $K5$. The binary multiplication operation will then proceed as follows. The operation code makes the control unit issue two successive signals (Y_1 and Y_6) to allow the multiplicand and multiplier to be fetched from memory, with the former placed into register A and the latter into register M (register B is assumed to be reset to zero).

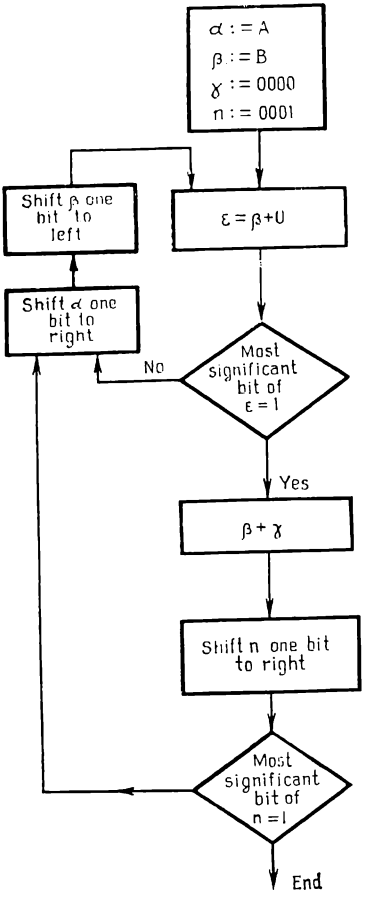


Fig. 7.6

Next, signals Y_4 shift the entered values in their respective registers, with the multiplicand shifted one bit to the left and the multiplier one bit to the right. If now the most-significant bit in register M turns out to be a 1, signal Y will place the sum of the contents of registers A and B into register C, while signal Y_5 will enter that sum into register B. If prior to the next shift the most-significant bit in register M is a 0, then the sum of registers A and B will be neither placed into register C nor into register B. With the operation completed successfully, signal Y_3 will send the contents of register C into the main memory for storage. The product has thus been accumulated in a number of intermediate operations, with none of their results brought into the main memory for storage. These intermediate operations are often referred to as *microoperations*, and the method of their execution just described is called the *hardware-control method*, as distinct from the earlier discussed software-control approach. Obviously, the same method can be applied to the execution of other complex operations, such as those involving floating-point numbers, etc. The overall

number of hardware-controlled operations is characteristic of the quality of a given computer instruction set. All things considered, the more operations a computer is able to perform under hardware control, the higher its computational speed and the milder its main memory requirements. The hardware control approach results, however, in more complex hardware, leading to higher computer costs and, in some cases, to poorer reliability.

The central processing units of computers of the ES EVM family, just as the IBM System/360 computers, are equipped with a powerful set of more than 140 various instructions. Over half of these constitutes what is generally known as the standard instruction set that includes the basic arithmetic and logical operations, conditional and unconditional control transfers (jumps and branches) and numerous variations thereof, easily realizable and frequently needed by users. A standard set supplemented with eight more instructions to perform decimal arithmetics produces a system of instructions for various accounting, finance, and such like business-oriented computations. There is also a large assortment of instructions to handle floating-point numbers which, together with the standard instruction set, provide a computer with the ability to execute a large number of elementary operations upon a single instruction.

In the IBM System/360, only computers of the "senior" class are provided with a complete set of instructions, while the instructions available to computers of the "junior" class are designed to perform either the business-related computations or scientific and engineering jobs. Unlike that, all computers of the ES EVM system (with the exception of the most "junior" ones) have a full set of instructions.

Control unit. A control unit can be treated as discrete automation device whose only distinction from other devices of its class is that in full accordance with the computer operating principle (that is to say, programmed data processing) it operates in two regularly alternating cycles—a preparatory cycle (during which instructions are fetched) and a main cycle (during which specific operands are fetched).

Both cycles commence with access to the main memory for appropriate instructions and operands. Since other devices (for example, external) may have to be accessed as well, the control unit operation must obviously be organized so that no further actions would be possible until the necessary instruction or operand(s) is fetched.

This can be achieved in two ways: either by directly monitoring the arrival of fetches, or else by allowing ample time for a fetch to arrive before attempting further operation. If the wait status lasts long, the first technique yields better results. If, conversely, the wait time is short and remains constant throughout, the advantages are on the side of the latter technique.

For the purposes of control and interchange of data between the central processing unit and main memory, resort is

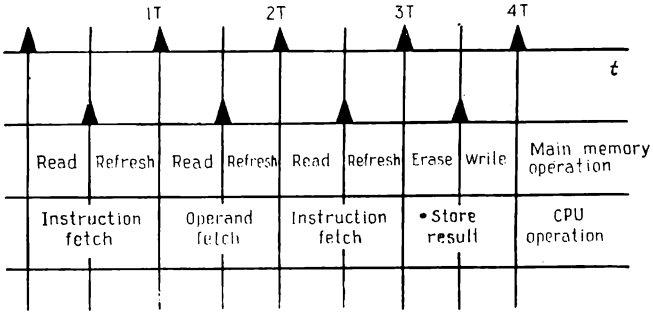


Fig. 7.7

usually had to the time delay method, whereby constant-frequency clock signals providing the time base for the entire computer system are simultaneously fed into the control unit and main memory. The first signal enables a fetch call and operation of the main memory, while the second signal trails it far enough to allow a response to arrive and then enable the appropriate control unit operations.

In this way, the main memory and control unit turn out to be rigidly timed, or synchronized, which fact gave this control method its name—*synchronous*. However, interchange of data between the control unit and other devices, as well as between these devices themselves, proceeds better under a different type of control known as *asynchronous*. Most modern computers use both these methods in combination, and have therefore come to be called *synchronous/asynchronous* machines.

One operating cycle of the magnetic-core main memory always consists of two successive sub-cycles (read/refresh and erase/write), and therefore the computer clock pulses are often arranged into a paraphase system, whereby each pulse is displaced one-half of a repetition period relative to the next. The timing of such pulses is shown in the upper part of Fig. 7.7 which also shows the system of timing and execution of elementary operations in a third-generation computer system. The main memory is timed as shown in the center portion of the diagram, while the central processing unit is clocked as shown in the diagram bottom. It would seem that once the repetition frequency of the clock pulses and the timing arrangement are known it is a simple matter to determine the computer speed. In practice, however, this can only be done with the simpler third-generation machines, because the speed of more sophisticated computers is much more difficult to determine.

Let us now consider the main phase of the control unit operation, the one in which the instruction code has been identified (decoded),

the corresponding operand has been requested from the main memory and is about to arrive. As is readily apparent, the control unit at this stage operates in much the same way as any other discrete automation device, and the reader is free to imagine the configuration of that device for himself, bearing in mind that whatever technical decisions are used to implement it, they will only affect the speed, not operation, of the device.

By the time the first digital computers became a reality, the discrete automation devices have already reached a sufficiently high level of development, which prompted the computer designers to utilize decisions already at hand. Later, however, more advanced principles of data processing characteristic of computers only were applied to the engineering of control devices, drastically changing them in the process. This was how the concept of microprogramming has evolved to become predominant in the world of computers. Today, microprogramming has a decisive bearing upon the choice of control methods in other branches of science and technology.

The concept of microprogramming consists in generation of the control signals through a specific use of binary code combinations (words) fetched from memory. These words determine the status of a set of busses running from the memory unit, so that an electrical impulse on a bus denotes a 1, and its absence denotes a 0. In hardware control, such pulses merely trigger complex logic circuitry which then responds with appropriate strings of control signals. With microprogramming, these pulses are, in effect, the control signals proper.

A simpler version of a microprogramming control unit is illustrated in (*a*) of Fig. 7.8. It incorporates a storage device with an input (address) and output (memory-fetched words) registers. Some of the lines shown running from the output register are later used for carrying control signals Y_1, Y_2, Y_3, etc. The signals may, for instance, be sent into the ALU or some other computer device. Other lines out of the output register are looped back to the input register and take part in the generation of the address for fetching the next word to be gated to the output register.

Apart from the lines already mentioned, the address is also generated with the participation of the lines running from the main memory, whose purpose will become clear later.

Once it accepts an instruction code from memory, the control unit can itself produce a succession of signals required to execute the microoperations postulated by the specific instruction. To prove it, assume that at a certain moment of time, with the previous operation completed and all the bits of the input register reset to zero, a certain operation code, say O_1, arrives from the main memory to the input register. This operation code, padded with 0's, will then be treated as the address of a certain location in memory in which

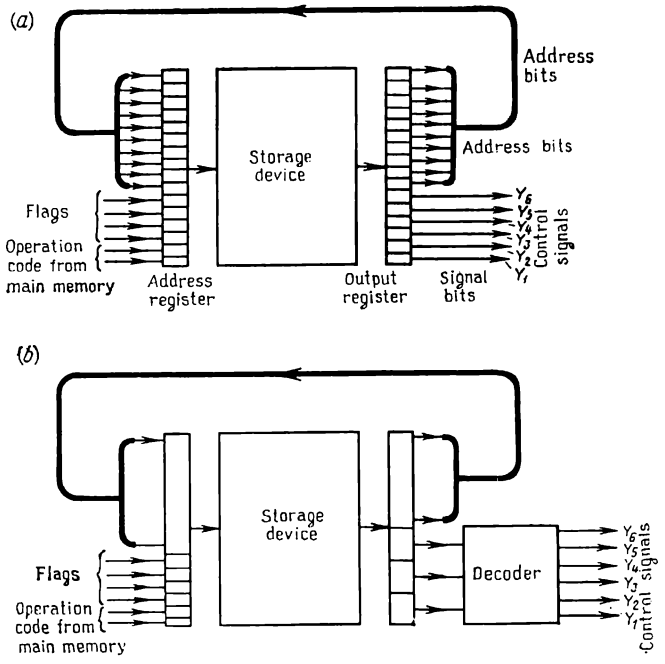


Fig. 7.8

can be a binary word containing a 1 in its first control signal bit (for example, Y_1), 0's in all other control signals bits, and the number A_1 complementing the O_1 operation code to the address of a next such word (next microinstruction). In this way, all the miroinstructions needed for the execution of the given operation can be fetched, after which the address part of the output word will again be reset to zero.

An important role in the above process can also be played by the so-called tag (flag) signals. For instance, in the earlier example of binary multiplication under hardware control, tag Π_1 served to indicate whether or not the signal to copy the contents of register C into register B was to be generated. As applied to a microprogrammed storage, this means that a microinstruction having a 1 in its Y_5 bit must be found at an address whose Π_1 tag bit is likewise a 1. Conversely, a microinstruction with a 0 in its bit Y_5 should be stored at an address having a zero Π_1 tag bit.

Significantly, all these "musts", "wills" and "shoulds" can be accounted for at the development stage, and take the form of an array of data frequently referred to as an *array of microprograms* and stored in a relatively simple device. All the necessary data are entered

into such a device for permanent storage during manufacture, and can thereafter be only "read" from it, for which reason devices of this class were termed *read-only memories* (ROM's).

A control system built around ROM's is very flexible, both in manufacture and use, because ROM's are standard devices, and therefore a transition from one repertoire of instructions to another necessitates only an appropriate modification of the data arrays entered into them, which is fairly easy to achieve. Besides, read-only memories can always be made to store check bits to ensure validity of all fetches made. All this is winning the read-only memories and the microprogramming control approach an ever widening field of applications in the computer world.

However, the simplest microprogramming control circuit illustrated in (*a*) of Fig. 7.8 is far from optimal, for if a large number of control signals were involved, a wide fetch size would become imperative, with 0's fetched in all but one signal bits (for the sake of simplicity, the case when several signals are used simultaneously is not considered). Therefore in practice a special device known as decoder is added to the control circuits, as shown in (*b*) of Fig. 7.8.

A decoder can be defined as a matrix of AND gates that has a total of n inputs and 2^n outputs and organized so that each out of 2^n input signal combinations produces a unique combination of the output signals. Decoders are widely used in automation, telecontrol and communications to convert code combinations into signals distributed among various objects. As Fig. 7.8 clearly indicates, the use of decoders in control circuits allows the word size of microinstructions to be considerably reduced, with as many as eight control signals obtained from only three bits of the respective part of the word.

Apart from the obvious simplicity, such a control technique offers the advantage of an easy modification of the machine instruction set through altering the contents of the read-only memories. Combined with other advantages, this has paved the way for a rapid changeover to the microprogramming control from the older control techniques now frequently referred to as purely hardware (not to be mixed with the earlier described hardware execution of logical operations!).

Hence, three control methods (software, hardware and microprogramming) can be identified. With the former, the source program must necessarily specify all the individual operations to be performed, down to the very elementary ones. With the second control technique, a programmer needs only to specify the more complex operations because all minor steps will be executed under control of various combinational logic circuits. Finally, the latter control method requires only a single specific instruction to perform all the relevant operations, but instead of a wide assortment of control hardware requires the use of only two types of standard devices (ROM's and decoders) which can easily be programmed to produce the necessary

sequence of control signals according to the user-written application. Besides, the very nature of ROM's as one-way devices makes them faster than random-access memory units, because of which microprogramming can compete with hardware control in terms of speed.

Central processing unit and main memory. Let us now consider the central processing unit (CPU) from the standpoint of its relationship with the main (random-access) memory. This is a very important aspect, for it conditions the structure of a computer instructions and, in the long run, efficient utilization of its memory.

The very first computers capable of a preprogrammed processing of data used a four-address instruction format, which means that apart from the operation code, addresses of operands and result return address they also contained specifications of the memory location at which the instruction to be executed next was stored. As computers developed, it was soon realized that if, during the execution of a prearranged sequence of operations, the relevant instructions are stored in memory one after another in a chain-like fashion, no need arises to specify the address of every upcoming instruction, it sufficed to establish the origin address of the instruction chain and have it placed into a special counter that would then be automatically incremented by 1 every time the current operation is completed. This was how the instruction counter (or program counter as it is sometimes called) has evolved to become later an indispensable ingredient of all computers.

The changeover to the sequential fetching of instructions by their address in the instruction counter (or to the so-called linear memory organization) has necessitated that the computer instructions be supplemented with yet one more special operation to write a fresh instruction set origin into the counter. This operation became known as unconditional branch (or jump), and is incorporated into the chain of computer operations whenever a certain sequence of instructions with continuously incrementing addresses has to be interrupted for a branch (jump) to a similar chain stored in a different memory area.

The next development was the introduction of the so-called *conditional jump* capability, whereby the decision as whether to jump to a new instruction chain or continue with the current one was made by the computer automatically depending on the result of the preceding operation (its sign mostly). Incidentally, it is this very capability that has turned a computer into a "thinking" machine.

The introduction of the instruction counter, conditional and unconditional jumps and other special operations of a similar kind marked the advent of the now classical architecture of digital computers, although attempts at its further improvement and development have never truely ceased. One of the more important innovations in this regard was a modification of the address part of the com-

puter instructions, both in terms of the number of addresses and the ways to specify them.

Number of addresses. Address-wise, competition has for a long time been going on among three basic types of computers. These are the one-address, two-address and three-address machines.

Referred to as *three-address* are computers in which the address field of every single instruction contains both the addresses of the second and first operands plus the result return address. Such computers are easy to program, but require special memory locations to store all intermediate computation results, even if a given result will never be used again except in the upcoming operation.

One-address, or *single-address*, computers are devoid of this limitation. With them, the instruction address field contains the address of one operand only, while the other operand needed to perform a given operation must be already residing in one of the ALU registers. In situations when that operand happens to be the result of a preceding operation, such a format of the instruction address part is very advantageous. But if this is not the case, a special fetch instruction is necessary to call in the other operand, which inavoidably makes the program longer.

The *two-address* instruction arrangement combines the advantages of both one- and three-address instruction formats. With it, the values of the address field of every instruction are conditioned by a special address flag (tag) included into the operation code, and can thus vary. For instance, in some cases the address field may specify the address of the second operand (and the result will then remain in the register), while in others it may denote the result return address (and then one of the operands will represent the saved result of the preceding operation).

The two-address system of instructions is very flexible, and is therefore used in all major computer systems of third generation, such as the ES EVM and IBM System/360. It is rather difficult to realize, however, for which reason the more simple third-generation computer systems (see Sec. 7.6) rely exclusively on one-address instructions. The three-address instruction system is presently employed only in those digital computers that have been specially tailored to perform complex scientific and engineering jobs. In newer computers, three-address instructions are fairly few.

Addressing. Digital computers are known to employ five basic addressing techniques. These are the direct, indirect (multilevel), explicit, indexed and relative addressing techniques.

With *direct* addressing, the address field of each individual instruction directly specifies the physical address of the relevant operand in the main memory. In contradistinction to that, *indirect* addressing implies that the first instruction, rather than specify the operand address, and contains the address of a certain intermediate

memory location at which that operand address is stored (several intermediate locations and several addressing levels are possible, and hence the name multilevel addressing). With counters used in the capacity of the intermediate memory locations, indirect addressing permits a wider memory area to be addressed without the need to increase the number of bits in the instruction address field, but requires multiple access to memory to fetch one operand.

Addressing is said to be *explicit* when the address part of an instruction is used to store a certain programmer-written code. Once a given instruction is decoded, this code is gated to one of the ALU input registers, the relevant operand being called *explicit operand.*

Indexed addressing implies that the basic address is appended with various indexes that can be formed and stored in special index registers and counters (hence the name *index arithmetics*). This addressing technique is very convenient for storing two-dimensional arrays, organizing loops, etc.

Relative addressing is essentially a development of the indexed addressing approach aimed at achieving a greater flexibility of the computer address system. With relative addressing, the physical address is obtained as a sum of the basic address specified in the instruction and a certain displacement, either of which may be indexed. Relative addressing is widely employed for the purposes of static allocation of the available memory among individual programs and users, as well as for organizing the memory protect capability. The latter is realized by sectionalizing the memory into pages and installing special keys to prevent unauthorized programs or users from writing data onto the page or pages allocated for a specific program or user.

Stack. The above-described method of data interchange between the CPU and main memory, whereby each instruction contains the operand address, is certainly one used most widely. But, this is not the only method, for there exist, for example, computer systems employing for the purpose special storages known as stacks.

Now, *a stack* is essentially a storage (built around flip-flop registers and magnetic-core RAM's mostly) external to the main memory and interposed as a buffer between that memory and the ALU. A schematic representation of a computer stack is given in Fig. 7.9, which shows it as a rack-like structure whose cells are filled with operands. The two top cells (*P1* and *P2*) contain operands needed for execution of a given operation. Once that operation is completed, *P2* is vacated, while *P1* stores the result which can either be gated to the main memory or pushed down when a new number is to be accepted from that memory.

A peculiar feature of the stack is that all data transfers in it are strictly conditioned. This means that the entire stack is pushed up whenever any of its upper cells is vacated. Conversely, if a number

has to be accepted from the main memory, the stack is pushed down (which gave the stack its other name, push-down storage), thus freeing cell *P1* for that number. Physically, of course, the process is somewhat different, but logically such an explanation is quite plausible. Besides, two more data transfers are possible in a stack. These are known as duplication (whereby the operand in cell *P1* is copied into cell *P2* by pushing the rest of the stack down accordingly), and reversal (whereby the contents of *P1* and *P2* are reversed, with the rest of the stack unchanged).

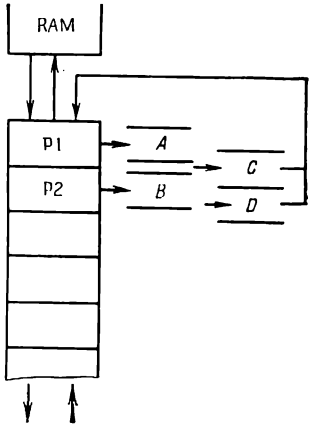


Fig. 7.9

Hence, the disposition of data in a stack is well known to the programmer at any given moment of time, allowing him to make use of addressless instructions in certain cases. For instance, if the result of $(A + B)/(C + D)$ is to be obtained, then A and B can be accessed in the main memory at their respective addresses, next an addressless ADD instruction can be executed, then C and D are fetched from their memory addresses, and finally the remaining ADD and DIVIDE instructions can again be addressless.

Not only does the use of addressless instructions save on the often valuable computer memory and time, it makes possible bulk (vector) data processing and use of translators from higher-level programming languages, especially when the so-called quick registers need to be employed.

7.4. Computer Speed

Various approaches can be adopted for quantitative evaluation of the computer speed. Thus, in synchronous/asynchronous machines the speed of individual operation is a variable quantity conditioned by a number of factors. Not only can there be short and long operations (such as, for example, addition and multiplication). One and the same operation can take different time to execute in various situations (in the case of multiplication, for instance, this time will be dependent on the number of 0's in the multiplier and in normalization on the number of displacements involved, etc.). If one takes into account the fact that the computer repertoire is constantly expanding, the complexity of assessing the computer speed becomes apparent.

One of the more advanced ways of revealing the actual machine speed and comparing different computers in terms of computational speed is to have them process a certain package of programs and then apply special coefficients to the results in order to assess the relative performance of these computers. However, different problems tend to yield different speed performance characteristics, and therefore this technique called benchmark is applied primarily to choosing the computer hardware for specific real-time systems. A convenient tool for evaluating a computer throughput regardless of the problems to be processed is provided by the so-called statistical sets, or mixes. These are obtained through accumulating the performance statistics on a very large number of computer problems to reveal the probability of a particular operation in the entire process of programmed data processing.

In recent years, by far the most popular among such mixes were the ones which the American mathematician Gibson has produced for scientific and engineering computer applications. These are known as the "Gibson-Mix I" which, although developed for second-generation digital computers, is still used on third-generation systems, and the "Gibson-Mix III" developed for and obtained on the IBM System/360 computers, and therefore very representative of the specific features of the instruction sets employed by these machines.

What, then, are the actual computer speed requirements? It should be stressed that high computational speeds were attainable, at least technically, already with second-generation computers. Examples are provided by the Soviet-made БЭСМ-6 and СДС-6600 (СДС-6500) computers of the early 60's which, with their one million operations per second, are still rated among the fastest mass-produced machines of their class. Computer users, however, are usually just as interested in computational speed as in other characteristics of their machines, and in this regard these second-generation computers are clearly inferior to the recent systems.

The need in a high computational speed prevails primarily in scientific and engineering applications. This is true even of off-line systems, let alone the real time ones in which a number of problems still defies a complete solution due to the inadequate computer speeds. But even then, a computer user is not disinterested in what the initial system price tag would be, what additional money would have to be spent to make it reliable, what operational costs would be involved, etc., to the extent that even the possibility to have fully-fledged problems solved might be outweighted by the prohibitively high extra spendings.

As regards other potential computer applications, the situation is still more complicated, for while in many cases the speeds attainable with second-generation computers seem to be acceptable, the hard-

ware efficiency is frequently not. As a result, the prime interest is towards an improved efficiency of computers—a goal that consists in the reduction of per-byte data processing and storage costs.

The ways that can be pursued to attain that goal are very reminiscent of the potential ways of bettering the efficiency of electric power systems. One is to build large computer installations and grids thereof, so that the considerable initial hardware costs would be more than paid for by the ability to serve a large number of users and customers simultaneously. The other is to reduce the costs of low- and medium-capacity computer systems, which in the long run would mean a lower per-byte cost of data processing. In the electric power industry the former way is more practical. Data communication nets, however, at least at this stage, are much less integrated than the electric power grids and therefore both these ways have to be followed, with various models of hardware built for computer systems of various capacity. A clear example of this trend is provided by the IBM System/360 and similar third-generation systems.

As is well known, the heart of the central processing units of third-generation computer systems are highly integrated microelectronic logic circuits. In mass production these circuits proved to be much more reliable than the discrete semiconductor components of the recent past. Besides, the new components, due to their near-microscopic dimensions, have negligible parasitic capacitances, and can therefore perform individual logic operations in fractions of a microsecond, or ten to fifteen times as fast as their second-generation counterparts.

True, random-access memories of third-generation computers underwent fewer changes. Yet, their control circuits did become more sophisticated and cheaper, making possible a switch to a more compact 2.5-dimensional memory structure characterized by shorter bus links. Combined with a speedier control capability, this yielded a four- to six-fold improvement in terms of data access time.

Under these conditions, it would be of interest to assess the potential speed of an electronic digital computer built around the newer elements and devices and utilizing a classical second-generation architecture, and then see how that speed could be altered to comply best with the demands of specific applications. Needless to say, the architecture of such a hypothetical computer would be assumed to be fairly sophisticated, with a fully-fledged hardware control over execution of complex operations and the entire computer, and full machine words used to fetch and process the necessary data (the variable length of instructions and operands typical of third-generation computers would have to be averaged). With these assumptions in mind, the overall time required to complete one com-

puter cycle could be found by totalling the average time intervals spent on instruction fetching (1 μs), decoding of instructions and their address modification (0.5 μs), operand(s) fetching (1.5 μs), execution (0.5 μs) and returning the result to memory (1.5 μs). On aggregate, one full machine cycle thus comes to 5 μs.

Hence, the typical second-generation computer architecture implemented with the newer elements and devices of the third generation can produce an average central processor speed of about 200 000 operations per second, the bulk of the time being spent on data interchange with the main memory.

Fortunately, the advances in microelectronics made much faster memories a reality. One example are the devices built directly around flip-flop (F/F) registers and suchlike elements and known as scratchpad memories. Back in 1964 when the IBM System/360 was launched, the cost of these devices was prohibitive, which forced the system engineers to settle on a compromise approach, whereby a magneticcore random-access main memory was augmented by a limited-capacity flip-flop register memory.

Buffer storages proved most successful in computers with a stack architecture, where the flip-flop registers constitute the stack "head". It is this very way that the engineers of the Soviet-made БЭСМ-6 computer went: a total of eight scratchpad registers in the stack head ensured a very fast access to intermediate computation results. In the IBM System/360, the stack structure was for a number of reasons found to be impractical, but scratchpad registers were still employed as the main memory buffers additionally entrusted with indexed arithmetic functions.

There is a total of twenty such registers, of which sixteen are fullword four-byte general-purpose registers, and the rest are floating-point doubleword registers of 8 bytes each. The general-purpose registers can be used as index registers to handle addresses and indices and store data needed for various logical and fixed-point arithmetics operations. The floating-point registers, as their name implies, serve primarily for floating-point manipulations.

The net result is thus a small-capacity (96-byte) storage to serve as a scratchpad for various operands. The addresses of its locations should, as before, be specified in the address parts of relevant instructions. With such an arrangement, the central processing unit of a conventional two-address structure produces instructions of three basic types. These are (a) instructions of the so-called RR, or "register-to-register" type in which both addresses are those of the register, (b) instructions of the RX, or "register-to-storage", type whereby the first address is that of the register and the second address is that of a main memory location, and (c) the SS, or "storage-to-storage" instructions whose both addresses represent the addresses of certain main memory locations. In addition to these, there are

also instructions of the two-address format with a directly-addressed first operand (the so-called SI instructions) and three-address (RS) instructions containing the addresses of two registers and one main memory location. Computers utilizing such a system of instructions are known as zero-plus-three address machines.

With the buffer registers used appropriately, the requisite number of the main memory read/write operations can be cut almost in half, the other half being replaced by a much faster register interchange of operands (which requires as little as 0.1 μs per one read or write operation). According to our earlier estimations, this may yield a 1.5-fold increase in the computer speed. Besides, the fact that these registers are relatively few makes it possible to address them by using only four bits per address (plus one bit in the operation flag). Hence, an RR-type instruction, for example, would be merely two bytes (or one halfword) long, making possible a more efficient utilization of the available computer memory.

On the other hand, it was soon realized that an effective use of buffer registers in the capacity of a scratchpad memory is far from easy, especially with automatic translation of the computer programs. For this reason, these registers are employed mainly as index registers. From this point of view, computer stacks offer more advantages and are therefore more preferable. It should be noted that there are now scratchpad memories with a capacity of several kilobytes built around flip-flop registers, but these are finding application primarily in computers of the "three-plus" generation, and are thus beyond the scope of our discussion.

Apart from the use of scratchpad memories, higher computer speeds can be achieved through a wider fetching of data from the main memory (up to two words at a time), as well as through combining the preparatory phase of the upcoming operation (which includes the instruction fetch, instruction processing and the operand fetch) with the principal phase of the current operation (which includes execution of the instruction and storing the result). In this way, the central processing unit speed can be raised by a factor of 1.5 to 2, although at a cost of a considerable increase in the processor complexity (specifically, a cluster of buffer registers has to be introduced to resolve conflicting situations arising when more than one computer device try to access the main memory at the same time).

Clearly, the latter method of making a computer faster can hardly be effective unless its memory operates in a linear (sequential) fashion, when no conditional jumps need to be made. Nevertheless, since in many applications conditional jumps are fairly infrequent, this technique can still be successful. Besides, the very idea of it appeals to many as a first step from the now classical sequential processing of data towards a more promising parallel-flow processing, which until recently has been unfeasible because of a prohibit-

ive complexity of the computer control involved. Presently, designers are pinning their hopes for higher computational speeds more and more on the parallel-processing approach, and not without reason: the Burroughs' ELIAC-IV computer system in which as many as 256 processors operate in parallel is reputed to be the world fastest machine.

As far as computer system costs are concerned, several ways can be adopted to reduce them. For one thing, use can be made (although at the expense of an appropriate reduction in speed) of the microprogramming control technique, with the necessary microprograms stored permanently in comparatively slow yet fairly cheap read-only memories. The next logical step would be the use of shorter words for main memory operations and shorter ALU registers. With this arrangement, however, binary words would have to be processed in a number of successive cycles, byte after byte or even bit after bit, which would inavoidably mean a return to a substantially sequential processing of data.

If such cost-effective models are incorporated into computer systems with downward program compatibility (as, for instance, is the case with the IBM System/360 and the ES EVM computers), they must be adapted for execution of instructions requiring the use of scratchpad registers. An easy way to achieve this is to have these registers replaced by permanently allocated main memory locations, although it would yield no gains whatsoever in terms of computational speed.

To illustrate the pros and cons of "controlling" the speed of computer systems through modifying their physical architecture without altering logical structure or average number of principal devices, consider Table 7.1. The table lists several characteristics of four

Table 7.1

Model	1020	1030	1040	1050
Main memory access width, bytes	2	4	4	8
Control	μ-programming	μ-programming	μ-programming	hardware
Scratchpad registers	Main memory locations	Thin-film RAM's	F/F registers	F/F registers
ALU processing	Byte-by-byte serial	Parallel	Parallel	Parallel, with some operations combined
Speed (thousands operations per second), with 32-bit operands in:				
Gibson-Mix I	9	63	300	500
Gibson-Mix III	10	40	200	300

models of the ES EVM computer family, which all employ a unified instruction set and individual component parts of comparable speeds.

7.5. Channels. Operating System. Data Management

The need to resolve the conflict between the growing throughput of central processing units and the clearly much slower progress of the data handling capacity of I/O devices prompted the designers of data processing systems to seek ways of organizing data interchange between the system processors and main memory in several parallel flows, without undue participation of the central processing unit (see Sec. 7.2).

One of the more practical alternatives is to have the necessary data interchanged during that part, or phase, of the main memory operating cycle during which the central processing unit is busy handling the already fetched data (this is known as cycle stealing). Else, the data interchange can be made to proceed independently of the current problem main program.

Data interchange between the main memory and peripherals of usual type proceeds under control of a standard program. Once the main program instructs it as to the number and type of the peripheral device, volume of upcoming interchange and the data array origin address, this standard program can carry on with the necessary operations independently of and concurrently with the main program. In the IBM System/360 and similar systems, these programs are called channel programs, while the devices implementing them were termed channels.

The channels are called *partitioned* if each individual channel program employs a separate set of hardware for its operation. If, however, one and the same assortment of hardware is used to run more than one channel program, that hardware is called a *channel with shared subchannels*, and the relevant programs are referred to as *subchannel programs*. As will be shown later, the former can be implemented as a microprogrammed automation device, while the latter—as a random-access memory with a processor-like control device. The feasibility and usefulness of a particular arrangement are dependent on the speed of the peripherals involved.

In computer systems such as the ES EVM, a considerable divergence exists between the speed-related characteristics of different I/O devices and data storage units (see Sec. 7.2). This necessitated the use of two basic types of channels: *selector* (fast) and *multiplexor* (slow).

Channels of both types employ a common logical concept and utilize similar operating principles. Out of a large number of peri-

pherals using their services (and therefore often called *users*), they can select a specific device with which to interchange data, establish a logical link with it and then execute the necessary program, which may include such operations as starting the device (if necessary), monitoring its operation, counting the number of bytes transmitted, addressing, and end-of-interchange status processing. Both types of channels have the hardware needed to perform these operations, including registers, counters, etc. In both cases, the contents of the latter must be updated either with the commencement and completion of the program, or else with each of its individual steps. But the principles of that updating, as well as the very mode of data interchange are quite different in channels of different types.

The selector channel usually serves peripheral devices capable of interchanging data at high rates, on the order of several thousand kilobytes per second. But more importantly, it monopolizes the data transmission links until the entire data array is transmitted and received—an operation referred to as *exclusive usage mode.* The multiplexor channel primarily serves devices capable of transmitting or receiving a few dozen or, at best, hundred bytes of data per second. At such slow rates, the use of an exclusive usage mode would mean a considerable underloading of the fast third-generation logic circuits, and require a large number of parallel channels for the information flow to be sufficiently dense. For this reason, the multiplexor channel operates in a substantially different mode known as *time-sharing*, or *interleaved*, or *multiplex mode.*

The concept of the multiplex mode consists in that the channel continuously and regularly scans (polls) the output (input) registers of its users, entering or retreiving in the process a certain unit of data (a byte mostly). The important thing is that the difference in the rate of operation of the peripherals and the channel is such that during a single cycle the latter can poll several dozen or even hundred of users with no noticeable delay to their functioning. Apparently, the multiplex mode implies organization of an appropriate number of subchannels, and execution of their respective programs in a virtually parallel fashion. Under such conditions, employment of a special hardware to achieve this would clearly negate all the advantages of time sharing. For that reason, the multiplex channel usually relies on unshared subchannels, and stores the data for a large number of parallel programs in a random-access device of a usual type, which is then referred to as the *multiplex channel storage* (MCS), or simply *multiplex storage.*

In operation, the multiplexor channel accepts the data to be interchanged with a specific user from the system central processing unit and places them into its storage pending contact with the user in question. When that contact is established, the data are retrieved from the storage and gated to the user appropriate registers. As soon

as the contact is terminated, the corresponding data, in a partially updated form (for example, with a modified byte count), is returned to the multiplexor channel storage until the next contact with the same user. In contradistinction to the selector channel, several microprogrammed automation devices can thus be said to exist in the multiplexor channel, with every operating cycle corresponding to a different device "configured" by the main memory prior to the commencement of the current cycle. Used as the address for retrieval of data from the storage is the address assigned in the given channel to the user served in the current cycle.

It should be noted that in certain situations the multiplexor channel can operate in the exclusive usage mode, although this means that a single user monopolizes all the channel facilities, thereby denying all other users access to the computer system resources. Special measures are therefore taken to minimize the duration of such an operation and restrict it to no more than 10 to 30 milliseconds.

A 4-kilobyte multiplexor channel storage with an access time of 1 μs permits organization of up to 256 unshared subchannels at a total data flow density in the channel of up to 40K bytes per second. With the channel in the exclusive usage mode, data can be interchanged at a rate of several kilobytes per second. For the senior models of the third-generation computer systems, such a data flow intensity is both desirable and necessary. But in junior models, the data interchange need not be so intensive in most cases, and therefore their multiplexor channels standardly share the CPU resources, which means that there is no separate MCS and its functions are taken over by the system main memory. It also means that no processing is possible as long as data are being interchanged, although the selector channel can, at least in principle, function independently.

Input/output interface. Computers of the IBM System/360 and suchlike systems have a unified (both physically and logically) system of links between their channels and peripherals. The system is known as the standard *input/output* (I/O) *interface*, which can thus be defined as a system of busses and links interfacing the channels with peripherals. The logical structure of such an interface can roughly be understood from the diagram of Fig. 7.1, which does give one an idea of the interface logic.

In more detail, the interface structure is depicted in Fig. 7.10. As can be seen, the heart of the interface are multi-wire busses to transfer data from channel to user (BUS-OUT) and from user to channel (BUS-IN). The busses can transfer data of three basic categories: the user addresses, signals to control the users, and the data proper. Identification of the data category is through the use of special identification signals carried by separate lines. Priority

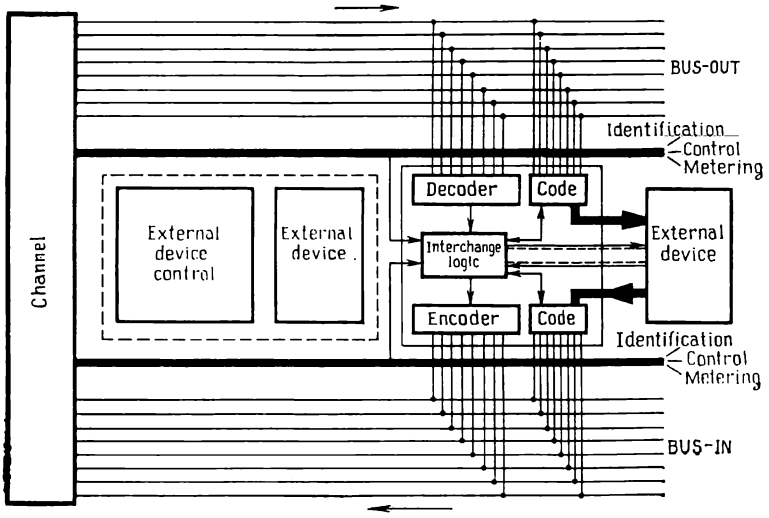


Fig. 7.10

and status of the users are identified by other signals sent through the control lines. Finally, the metering lines aid in monitoring the operation of the system users.

One of the basic functions of any interface consists in transmission of user addresses for the purposes of a correct data interchange. These addresses are identified by the decoder (a device converting the input code combination to an output signal) associated with each of the user outbound lines. The decoder illustrated in the figure can be termed distributed, because its individual parts are distributed among the individual users and each such part responds to no code combination other than that of associated user, which in effect represents that user address. An 8-wire bus system can accommodate as many as $2^8 = 256$ addresses. It should be noted that the system in question has a two-level decoding arrangement, whereby the eight first-level users shown in Fig. 7.1 are first identified, after which all other users are identified in groups of 32. If a given user is to receive certain data from the interface (channel), the decoder must first identify that user address before opening (together with the data interchange logic) a transmission gate allowing the next data byte to reach the destination. Similarly, the decoder can put out a user address to BUS-IN, with the result that as soon as appropriate acknowledge signals are received the necessary information will be gated from that user to the interface (channel).

This, then, is the general outline of the logic of the user-to-channel link passing through the interface. It is realized by the user control

circuit shown in Fig. 7.10. The user control circuit can be an integral part of the user (and is then referred to as the standard channel interface unit), or take the form of a separate device known as controller. Hence, the user control circuit is intended to ensure compatibility of channel and user logics. It can be used to connect to the standard interface any new peripheral device (user).

Apart from the interface, peripheral devices can access the CPU channels through a system of interrupts. But before we come down to that system, it is worth noting that not all newer computer systems developed after the IBM System/360 have their interfaces organized as described above. Thus, the GE-600 systems utilize special 1/0 processors with a total of 32 similar-type channels for each of the peripheral devices (there can be up to four such processors in a single system). In the B-6700 computer systems of Burroughs, which have a highly developed modular structure, the I/O processors have only four identical channels per user, but the number of processors is not limited, etc.

Interrupts. The growing complexity of data processing computers and their functions has necessitated the development of a system of measures that would promote a better organization of computer control and help improve its reliability.

An *interrupt* can be defined as transfer of the system from one program to another by a special signal, regardless of the status of the program being interrupted. Interrupts are classed into two major categories, *internal* and *external.* External interrupts were first to be used. External interrupt signals were used primarily in real-time systems for organization of individual operating cycles and jumps to higher-priority programs (hence the name priority interrupts). It was soon found out, however, that various reasons may lead to internal system interrupts. It was then decided to have all interrupts, external and internal alike, classed according to their priorities. Thus, in computers of the IBM System/360 there may be the following types of interrupts.

Machine-check interrupts. Virtually any computer is equipped with special circuits designed to monitor the validity of computer operations (an example is the parity check during carry operations). In earlier computers, all signals developed by these circuits lead to an abnormal end (ABEND) of all computer activities. Today, an interrupt in the main program execution by a machine check circuit signal merely forces the computer central processing unit to switch over to a diagnostic routine, the result being known as a machine check interrupt.

Program interrupts. Program (or program-controlled) interrupt signals are generated every time the main program uses an invalid command (instruction) or an invalid operand format (invalid specifications). A transition to a new program is necessary in such situa-

tions in order that the computer operator or programmer could be informed on the nature of error.

Supervisor-call interrupts. A supervisor is essentially an executive program designed to maintain a liaison between the main programs and channel programs. Of course, supervisor calls could be executed through conventional conditional jump programs. The use of a special facility for the purpose is, however, in many respects more practical. Supervisor-call and program-controlled interrupts are assigned equal priorities because under no conditions can they occur simultaneously.

External interrupts. Interrupts of this kind are widely used both in real-time and batch-processing systems. In the latter case, the external interrupt capability allows the operator to intervene into processing of a current batch in order to make appropriate corrections.

Input/output (I/O) *interrupts.* In situations whereby one and the same processor executes the main programs and assigns tasks to the channels, it is imperative that special facilities be available which would enable the processor to discontinue the currently processed main program in order to check on the progress of a certain channel program or issue fresh instructions to one of the channels. Used as such facilities are the input/output interrupt signals produced each time a preset volume of data interchange between the channels and subchannels (or users) has been completed.

Hence, there are five interrupt classes and four interrupt priority levels. The mechanism of interrupts is fairly complex, especially if the number of potential causes for interruptions is great. An interrupt, as the name implies, does not mean that the interrupted program is abandoned altogether. Rather, it means that the program is only temporarily discontinued, and will, under certain conditions, be returned to. Note that execution of the program will not start all over again, but will rather commence where the interrupt had occurred. For this reason, it is essential that the contents of all the registers that served a given program at the instant of interrupt (including the contents of the instruction counter, general registers, etc.) be preserved, or "saved", so that they could be restored once the program is returned to. This is made easier by the use of the so-called standby registers in which the old program (A) can be stored, or a new program (B or C) can be executed.

Fig. 7.11 shows an exemplary interrupt diagram. Note that a situation may arise when a new program (B) would be interrupted by a higher-priority program (C), so that the original program would be returned to through a number of intermediate steps. Since it is clearly unfeasible to have special standby registers provided for all possible intermediate steps (or priority levels as they are sometimes called), either the number of these steps (levels) has to be limited to a certain minimum, or the main memory must be made

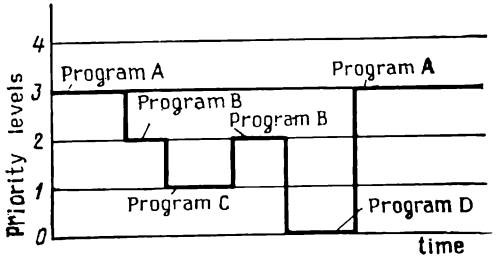


Fig. 7.11

to store the register contents. As is usual with computers, this can be achieved by using either a hardware or software (program *D*) approach. In today's environment, multiple-level interrupt capability is characteristic of only control computers, which can have as many as seven or eight interrupt levels. In general-purpose computer systems, the interrupt hierarchy is seldom more than two levels deep, and is typically one-level only. This means that in such computers no special registers are provided, and all interrupts are hardware-controlled by the main memory which, in its specially allocated locations, stores the so-called program status words that contain information on the current program address and certain other characteristics. Each time an interrupt occurs, the program status word (abbreviated PSW) stores the error code which arrives together with the interrupt signal and is employed to launch special executive routines known as *interrupt processing* (or simply *interrupt*) *programs*. It is these very programs that handle all subsequent operations for transferring control to a new main program or returning it to the old one if a given interrupt necessitates no such transfer.

External interrupts are signalled by a special register which accepts signals from various sources to each of which a particular interrupt procedure may correspond.

In order to preclude program interrupts by unrelated sources and to permit certain specification violation and such like options, the programs are usually "masked" from these sources. Masking is ensured by a special instruction for each of the input/output channels, each cause of interrupt (such as an overflow, etc.), as well as for all the external sources and all machine check circuits simultaneously.

Interrupts is the principal tool of implementing the computer operating modes (see Sec. 7.1), including batch processing, time sharing, real-time processing, etc. It is also the basic means through which the data processing control facilities, including the operating system, implement their functions.

Operating system. The complexity of controlling the third-generation compute systems (which, among other reasons, is due to

widely divergent data-handling speeds of their component parts) makes purely hardware control clearly inadequate. A situation therefore arises whereby the hardware control facilities need urgently be supplemented with a system of software other than the programs for processing the data by executive functions (or, in other words, a system of programs that have available no information other than that derived from the main processing programs).

As such systems came into being, various names were applied to them. Thus, the Burroughs corporation used the term "Central control program", while the ICL named their system "Executive", etc. The most popular, however, happened to be the term "Operating system" first used by the IBM people. This latter term ever since has been widely applied in data processing.

Not only there exists a difference of opinion on how to name the operating system, but also on how to define it. Thus, some argue that the operating system does not embrace algorithmic translator programs, although their specific features are, generally speaking, akin to those of other service programs. Yet, the basic trends in the development and evolution of operating systems have by now become quite apparent.

Continuing the analogy between data processing and processing branches of industry, a computer system can be viewed as a kind of a processing center (the name applied in machine-tool industry to a group of interrelated tools capable of completing the processing of a semi-finished article). In such a center, the operating system can be likened to a group of robots of various ranks servicing and managing it at all hierarchy levels, from feeding in the semi-finished articles and unloading the finished goods to the performance of administrative, managerial, scheduling, planning and book-keeping functions.

The validity of the above analogy is attested to by the very names applied to both the operating system component parts (such as supervisor, scheduler, editor, etc.) and its level (higher, medium or lower). Indeed, operating systems of the lower level perform only an absolute minimum of operations essential for a software control of a computer system functions (such as interrupt processing, servicing of input/output demands, etc.), with all other data processing control functions tackled by the operator. Medium-level operating systems are entrusted with a much broader range of functions.

Multiprogramming. The multiprogramming option permits automatic transition from one program to the next, thereby ensuring a highly efficient utilization of the central processing unit capabilities in working with much slower input/output devices. The number of these programs, however, is fairly small in most cases, and their usefullness is to a considerable degree contingent with the intervention of a human operator.

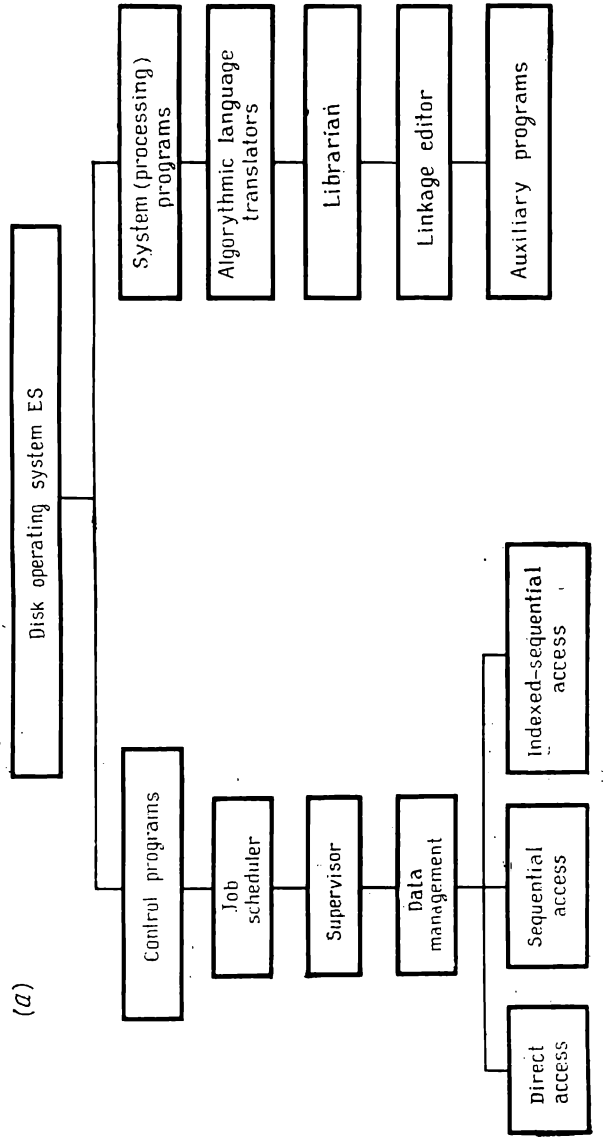
In the case of a higher-level operating system, the basic responsibilities of the operator are restricted to supervising its progress, installing tape reels and disk packs, and such like functions (which, incidentally, are also performed according to the operating system instructions). The operating system is responsible for all other operations and functions, including the overall scheduling of the computer system and its individual parts and devices, supervision over the execution of the planned workload, troubleshooting, delivery of finished goods (data or information) and, if necessary, billing the customer with the cost of the machine time spent. In doing so, the operating system relies on many advanced methods of planning and management.

Implementation of a successful operating system is an extremely labor-consuming job requiring thousands of man-hours of intensive work of top-qualification specialists. However, powerful multiple-purpose computer systems possess such a broad range of potential capabilities and resources as to make application of even most complex economic and mathematical tools to their scheduling and management worth the effort. In this regard, the development of computer systems may be likened to the progress of power system automatics which initially served only individual power stations but has since gone far beyond their constraints.

In the way of an example, consider two recent operating systems used in the Soviet Union: a medium-level disk-oriented operating system DOS ES shown in (*a*) of Fig. 7.12, and a higher-level operating system OS ES illustrated in (*b*) of the same figure. Both systems are intended for batch processing of data, and are expandable through the addition of remote processing. Two kinds of programs clearly stand out in either system: the so-called system (or processing) programs applied to the preparation of any fresh (user-written) program, and control programs responsible for data processing proper and executing such functions as input/output processing, transfer of data in and out of external storages, etc.

In the operating systems under discussion, problems are prepared for execution in several steps. This is done to permit a maximum flexibility in choosing a particular program compilation technique or using other computers programs, and ensure usability of previously written programs (or at least segments thereof). To this end, use is made of a module concept as a major ingredient of any program.

Source module. The source module may be written in any algorithmic language applicable in a given system. Moreover, various parts of a problem may be written in different languages. The source module is then translated to become an *object module.* The following step is called editing, and consists in the establishment of appropriate linkages between individual object modules (the process being known as linkage editing). The result are the so-called *absolute*


(a)
Disk operating system ES
Control programs
Job scheduler
Supervisor
Data management
Direct access
Sequential access
Indexed-sequential access
System (processing) programs
Algorythmic language translators
Librarian
Linkage editor
Auxiliary programs

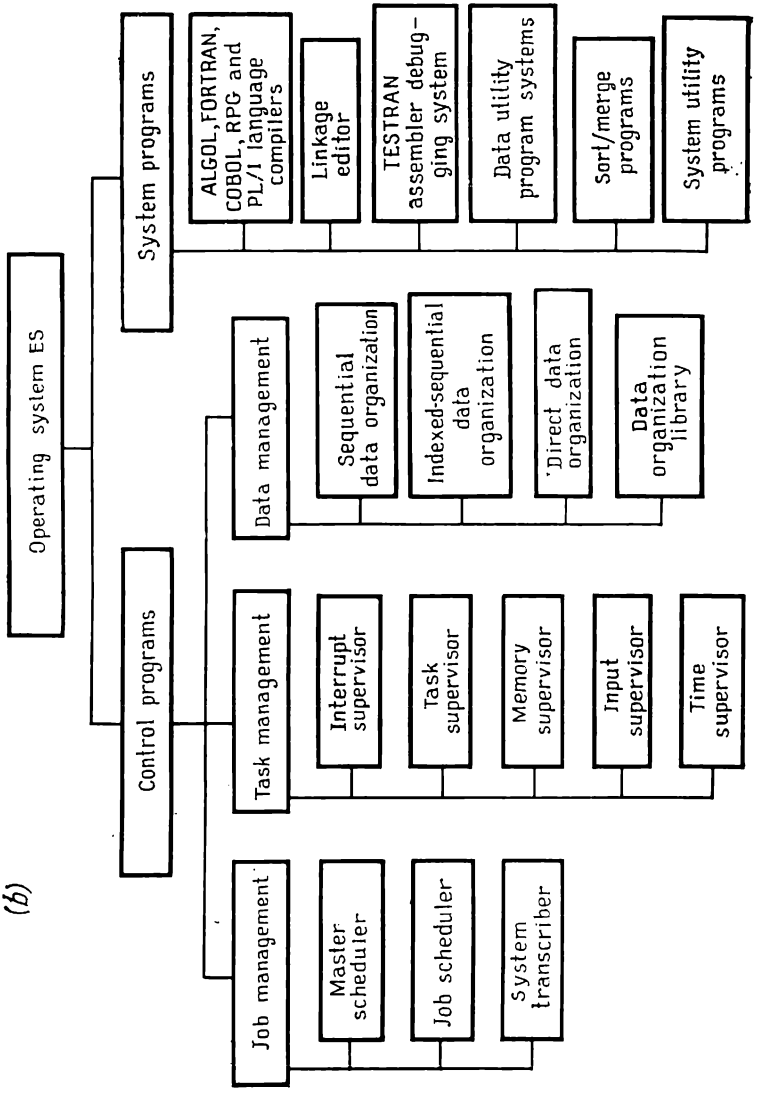

(b)
Operating system ES
System programs
ALGOL, FORTRAN, COBOL, RPG and PL/1 language compilers
Linkage editor
TESTRAN assembler debug-ging system
Data utility program systems
Sort/merge programs
System utility programs
Control programs
Data management
Sequential data organization
Indexed-sequential data organization
Direct data organization
Data organization library
Task management
Interrupt supervisor
Task supervisor
Memory supervisor
Input supervisor
Time supervisor
Job management
Master scheduler
Job scheduler
System transcriber

Fig. 7.12

modules, or *program phases*, now ready to be processed. Throughout the module preparation steps, the programmer has access to appropriate libraries which he can use to supplement his modules with both the user-written programs used earlier and a large assortment of standard programs compiled and prepared by the operating system originator. This completes the program preparation procedure, and the programmer now needs only to append his deck of punched cards with specially prepared control cards which use a special language to relay all the necessary control information to three basic parts of the control program responsible for the management of jobs, task and data.

Now, a *job* can be defined as a basic unit of workload which the data processing system must fulfill under control of the operating system. Individual jobs are completely self-contained, and can therefore be performed concurrently with other jobs. Every job includes several steps executed consecutively one after another. Each job step corresponds to a unique main program, but may also be supplemented with a number of auxiliary programs of various kinds. In the latter case, the result is known as task, which takes place each time the system commences execution of a next job step. Apparently, a system processing several jobs will have available an appropriate number of tasks, each with its own set of data. This is the way the "job-task-data" hierarchy of the control program shown in (*a*) of Fig. 7.12 results.

Existing concurrently in the computer systems, various tasks inavoidably compete among themselves for access to its resources (central processing unit, I/O devices, etc). Therefore one of the operating system primary functions is to so schedule the system activities that the demands of individual tasks for these resources would be fully met. On the other hand, the operating system must also strictly coordinate the subsequent course of actions, in order that no unrelated events could have the information flows of different tasks mixed, bring about a loss of information, etc. To understand how this can be achieved, consider a batch processing example, whereby several individual jobs have been grouped into a single batch to form what is known as the *input job stream*.

Once the system is activated, control is taken over by the *job scheduler*. Using special characters known as delimiters, the job scheduler reads the deck of cards written in the job management (control) language, organizes job queues in accordance with the operator- or programmer-specified priorities, analyzes input/output requests, allocates appropriate I/O devices to serve these requests, separates the relevant jobs steps and passes them over to another part of the control program. At this stage, the computer system operator can intervene with the job scheduler progress in order to augment the operating system with a more powerful facility known

as the master scheduler—a program capable of executing a large number of the operator instructions regarding changes in the priorities and other system modifications (for instance, the addition of new I/O devices), as well as of supplying the operator with detailed information on the progress of data processing in the system

Supervisor. The part of the operating system that takes over from the job scheduler to manage all the system internal functions is usually referred to as *supervisor.* Depending on the level of a given operating system, there can be a common supervisor (as in the DOS ES) or several supervisors (as in the OS ES) performing a wide range of functions. One of the most important of these is control of the input/output processing. Since in the multiprogramming mode the requests for input or output of data may be originated by more than one task at a time, giving rise to conflicting situations of all sorts, it has been established that all the input/output operations will proceed through a single channel incorporating the supervisor. To this end, these operations are declared privileged, and are not executed except as the supervisor calls.

To be able to respond properly to the input/output calls and to ensure an efficient utilization of the central processing unit capabilities, the supervisor must monitor the progress of each single task on a continuous basis. The supervisor does that with the help of the so-called data control blocks created for each task to include all information on the requisite system resources, allocation of the memory fields, etc. Once a given task gets underway, the supervisor continuously monitors its current status, which depends on the ability of the task to utilize the central processing unit. If the task is prepared to make use of the CPU but fails to do so, it is considered to be in the READY state, and is transferred to the so-called ACTIVE state at first opportunity.

Conversely, if a task currently utilizing the central processing unit (and therefore referred to as active) makes a call for a certain system resource (for example, for some I/O device channels), it will be transferred to the WAIT state until completion of data exchange with the resource in question, when it again will be transferred to the READY state. In some cases, the WAIT states can be programmer-specified (for example, to wait for teleprocessing data). With such an arrangement, the supervisor can always have available those tasks which are ready to utilize the central processing unit while other tasks are busy receiving the necessary data.

Apart from the above-mentioned functions, the supervisor also processes input/output interrupts, keeps track of the system synchronization and the amounts of time spent on the solution of various tasks, and performs all system re-start operation after an abnormal termination.

One final function of the control program is data management. By managing data, the control program enables the system programmers and operators to handle the vast (but yet invisible to human eye) archives of data, which in modern data processing systems are organized and stored on magnetic disks, tapes and drums. Like in conventional archives, the data stored in these archives are sectionalized into individual units of storage known as *volumes.*

As applied to computers, a volume can take the form of a magnetic tape reel, a magnetic drum, or a magnetic disk pack. Whatever the form, all volumes share one common feature—each is provided with unique magnetically-written and man-readable labels which enable the operator to identify the requisite volume and prepare it for use when necessary. But an arrangement whereby the operator of a powerful data processing system has to remember where to find the source material for a particular problem can hardly be assumed practical. Just as impractical would be to have the system programmers keep record of that information, especially if a given system handles a large number of various problems and its memory and storage capabilities are limited and need to be used efficiently and sparingly. For these reasons, all multiple-purpose computer systems under consideration are equipped with special data management facilities in the form of special programs, appropriate data management languages and, in some cases, special hardware.

Data. The vastly divergent nature of data making up scientific, engineering, technical and economic information cannot but have a certain bearing on practical implementation of the data management facilities. Besides, an account has to be made in this regard of the different addressing techniques employed to access different computer devices. As was pointed out earlier in this chapter, retrieval of data from sequential-access devices (such as magnetic tape units) is only possible by addressing whole segments of appropriately labelled data, whereas with direct-access devices it is possible to specify the information cylinder (or even the track) number.

The common practice is therefore to employ various access methods according to the type of data and its storage media used (Fig. 7.12*b*). Application of all these methods is based on a unified data structure organized into separate arrays, or files. A file is defined as an organized and named collection of logically related data records, which can be of virtually any size. In some cases, a single volume will incorporate several files, while in others a single file will reside in more than one volume. The files are uniquely named to facilitate their automatic identification by means of special tables of contents that usually take the form of a number of volumes. These volumes are assigned more detailed names, including specifications of a cylinder, disk or track number or even a still smaller body of information known as *record.*

A record is a logical object conditioned by the nature of the relevant problem and treated as an inseparable whole, i.e. as a collection of related items of data treated as a unit and requiring no further partitioning to be located. A convenient example of a record in scientific and engineering data processing is provided by the catalog specifications of a certain item of equipment invoked for processing by that item catalog number. Fixed-length records are adapted best for use in computer systems, because they offer the ease of data packing in the memory and storage. However, use can also be made of variable-length records, although the length must be explicitly specified by special data management (control) language statements known as DD (for data definition) statements.

Each record is preceded by a unique *identifier* and a *key*. The key serves to identify the data in a task and may contain such information as the device type, its number, etc. The identifier helps to address data in the system and may, generally speaking, be very long. The memory requirements for storing the indentifiers can be minimized by collecting individual records into blocks, with only one identifier provided for each block of records. Once loaded into the data management (control) program main memory, the blocks are deblocked.

Most identifiers are of a compound type, specifying such information as the volume number, the number of its cylinder, the track in that cylinder and the record on that track. In this way, a search tree can easily be organized. The names of data sets can likewise be compound. A system using such names can make it unnecessary for the user to specify the physical address at which a particular unit of data is stored. Instead, the user needs only to specify its logical address (name) which the system will then utilize to locate the physical address and instruct the operator to get the requisite volume ready.

With sequential-access devices, such a system allows certain sets of records to be addressed. With direct-access devices, addressing down to individual records is possible. However, a somewhat different access method is often more useful with these devices. It is known as the indexed-sequential access method (ISAM), and consists in that records can be loaded individually but retrieved in sets in the order of pre-assigned indices, and vice versa. The implied advantages need hardly be elaborated on here, but it should be stressed that ISAM can only be implemented with magnetic disk storage units.

There exists yet another method of data storage, whereby the stored data is organized into partitions. This method is employed primarily for storing programs and compiling libraries thereof.

All information related to the access method and data storage organization is specified by the programmer in the same way as the job and task management information, i.e. by means of control

cards placed into the input stream. Transition from one method and array to another is automatic, except that the operator replaces magnetic tape reels and disks following the system instructions.

Modes of operation. The operating systems under consideration can operate in the following modes:

(a) *primary control program* (PCP) mode. This is similar to the operation mode employed by second-generation computers, with all the system resources subordinated to execution of one task only;

(b) *multiprogramming with a fixed number of tasks* (MFT), whereby the system resources are distributed among a pre-set number of tasks (not more than three in DOS and fifteen in OS);

(c) *multiprogramming with a variable number of tasks* (MVT), in which some or all tasks can form sub-tasks, with the result that the number of tasks concurrently processed in the system becomes a variable quantity, and can reach 17 in DOS and as many as 256 in OS.

Although completely adequate to meet batch processing requirements, the above modes can be further developed to include teleprocessing. Also, real-time processing is possible through application of the so-called real-time monitor program with which an external interrupt causes transfer of control from the batch processing control facilities to programs designed specifically to tackle such like situations.

Apart from the operating system discussed above, there exist other similar systems featuring more or less developed capabilities. What unites all sophisticated operating systems is that they require large memories to be successful, to the extent that a part of the system has to be placed on disks or even tapes. But even then, the main memory must be quite of an appreciable size (no less than 256K bytes for higher-level systems).

7.6. Mini-Computers

Minicomputers can be said to constitute a distinct class of machines whose most typical features are a reduced word size (between 8 and 18 bits per word), a simplified (due to the exclusion of complex operations) instruction repertoire, and compactness (many minicomputers are designed for desk-top installation). First mini-computers came on the market in late 60's, when it was hoped that lower-level models of general-purpose computer systems would be able to fully meet the demand for process control and other specialized application. While that hope has never truely materialized, minicomputers are now produced in much greater numbers than large general-purpose systems.

The success of mini-computers is largely due to their reliance on the advanced software control concept (Sec. 7.3), with which a sim-

ple unassisted arithmetic/logic unit (ALU) can be adapted to execute all operations (even the more complex ones) that the larger installations need special hardware to perform. This has been facilitated by the use of short computer words—an arrangement also beneficial for improving the computation accuracy standards, because it permits an easy organization of double-precision computations. All in all, the potential capabilities of mini-computers turn out to be on a par to those of their larger counterparts, although at the expense of computational speed and programming complexity.

In the world of computers, such an emphasis on software (rather than on hardware) is sometimes referred to as *trading structure for procedure*, or *hardware for time*. In certain environments, this approach yields better results, the more so that the high speed characteristics of modern electronic circuits and devices bring the computational time down to quite acceptable levels. On the other hand, with the hardware costs declining, fairly cheap mini-computers become a reality, especially in view of the benefits brought about by mass production.

The fact that mini-computers require a large volume of software support necessitating appropriate investments is only a minor drawback, for it is usually outweighed by the wide assortment of standard programs available optionally to the mini-computer buyer. In large-scale production, the percomputer costs of generating and disseminating this hardware turn out to be quite moderate. For this reason, compared with the hardware, the program texts, programming manuals, programs prepared on punched cards and suchlike support material embraced by the term software occupy a larger segment of the computer market. The eventual result are computer systems that make it possible to achieve a required objective at very few extra costs, primarily through the effort of designers and programmers. All this makes mini-computers quite a promising development.

Originally, mini-computers were almost exclusively intended for process-control applications. Today's mini-computers tackle a much broader range of jobs, from computer-aided solution of various astronomical problems to accounting, billing and payment calculations. Yet, a considerable proportion (30% to 40%) of these machines is still utilized for control purposes, with some units designed especially as part of non-standard aggregates of various sorts, or as a replacement for conventional automation devices.

Most widely used are systems incorporating external storages of two basic types—special magnetic disk (with a capacity of between 1 and 2M bytes) and magnetic tape miniunits. The computers integrated into such systems can communicate with a large number of external devices interfaced to trunk busses of shared channels (Sec. 7.3). Special support hardware has also been developed to allow

mini-computers to perform multiply/divide (and even floating-point) operations under hardware control.

Thus, a mini-computer supplemented and supported by various facilities can be turned into a fully-fledged high-capacity computer system. Alternately, the user may decide against the use of devices that speed up computations, and instead employ other hardware designed, for example, to ensure communication with the controlled object. What he will have then is an automatic or automated management control system built around a mini-computer.

Typical examples of the above approach to the use of modern mini-computers are the Soviet-made system ACBT M-6000 and Hungarian-made system 1010B. The heart of the former system is a central processing unit operating with words of 16 binary digits each, which allows up to 32K of words of the same length to be internally stored and indirectly addressed. The system memory cycle is 2.5-μs long which, according to Fig. 7.7, makes it possible to fetch a number from memory and add it to another number stored at the ALU register during 5 μs (using the direct addressing technique). Multiply/divide operations in the system are software-controlled, but a special device known as "arithmetics expander" can be optionally added to the machine in order that the same operations could proceed under hardware control (7.3).

System 1010B is likewise using 16-bit words at its input and output, but the internal processing is byte-by-byte serial. The computer main memory cycle is 1-μs long, and fetching is 1-byte wide. The computer has no instruction counter, and the address of the next operand is obtained by incrementing by one the number fetched from a special location of the main memory. Therefore the addition of two 16-bit numbers requires some 7 to 8 μs. Multiply operations, however, are hardware-controlled, and any two bytes can be multiplied within a stretch of 9 to 10 μs. On aggregate, both machines have similar throughputs (defined here as the average speed times the number of bits in one machine word), and are in this respect comparable with such computers as M-220 and БЭСМ-4.

Both machines can be interfaced to a large number of external devices, including those for communication with the controlled object. Thus, system 1010B can operate with many peripheral devices commonly called "real-time cabinets", which house the equipment designed to accept signals from the contacts of various relays and generate appropriate control signals. The signal paths are collected into 16-digit groups each of which corresponds to a unique binary word. The latter are assigned addresses, of which there can be as many as 2^{16}. The computer can accept the words as the input device numbers and analyze them on a digit-by-digit basis to determine whether or not a particular relay has been energized. Alternately, it can generate response words to be output to respective

relay groups. The one in the appropriate bit of such a word will then make the corresponding relay close its contacts, while a zero in the same bit will not. The relay contacts are wired to special terminals for connection to appropriate actuators or mechanisms. If necessary, the computer circuitry can be electrically isolated from the control signal paths (an arrangement known as "dry contact"). Besides, the output relays can be of a latching type, capable of remaining in a certain state even after the computer signals are removed (as long as power is applied).

Thus, a standard digital computer can provide a basis for implementing a management control system of virtually any configuration, with the system capabilities dependent not so much on its hardware as on the software (programs) used. If no alternations of the software are expected to be necessary during the entire system life, it can well be placed for permanent storage into read-only (rather than random-access) memory devices, which would effectively mean a transition from a purely software control to microprogramming.

Recently, many computer manufacturing firms have been marketing optional RAM chips for various software applications. The systems employing these devices have come to be called "firmware-controlled", as distinct from conventional soft- and hardware-controlled systems.

The advances in the field of microelectronics, and especially the advent of large-scale integrated circuits (or LSI chips as they are commonly called), have led to the appearance of entirely new computer devices known as *microprocessors.* A microprocessor is an LSI chip measuring 4 by 4 mm and incorporating an ALU for 4-, 8- or 16-bit words, an instruction decoder of some sort, and between 8 and 10 scratchpad registers. The functions of the microprocessor main memory can be performed by any of the existing devices. Most frequently, however, programs are stored in solid-state read-only memories pre-fabricated to the user specifications. The resulting structure is reliable, low-cost, and can successfully be used for the purposes of process and management control. Known as micro-computers, these devices are winning an ever wider field of applications.

In recent years, high-level computers are often used in combination with smaller machines to achieve a more flexible computer system structure, improve reliability and simplify the mathematical support apparatus. Such a combination is organized by means of special "channel-to-channel" adapters or direct control links. Situations are not infrequent whereby a full-scale computer operates in conjunction with two or more mini- or micro-computers, all of which share a common memory field.

REVIEW QUESTIONS

1. What were the primary applications of second-generation computers? How does each of these applications condition the requisite computer capabilities?
2. What logical structure of data do the digital computers of the ES family rely on? How many bits of data are there in one byte, one fullword, and one doubleword?
3. What is the logical structure of third-generation data processing systems? Define a central processing unit, a channel and a memory. How do these devices interact between themselves and peripheral devices?
4. At what rates are the data interchanged between the computer system nucleus (CPU, memory, channel) and the peripheral devices of various types? Draw up a table of these rates and give a comparative analysis.
5. What kinds of arithmetics are the CPU of the ES computers capable of handling? What arithmetics are best applicable for scientific, engineering and business-related jobs?
6. Name the basic functions of the ES computer channels. What role do the channels play in the process of computations? How are the channels of higher-level ES EVM computers implemented? How are they implemented in lower-level models of the same family of computers?
7. What data processing modes are utilized in third-generation computer systems? Give a brief characteristic of each of these modes and their potential uses.
8. What types of operating systems are available with the ES EVM computers? What is job, task and data management (control)?
9. How can microprogramming be defined? What are its applications in third-generation computer systems?
10. Give a definition of a mini-computer. How can the relatively high speed and low cost of mini-computers be explained?

Chapter 8

Emergency Control of Power Systems

8.1. General

Electrical installations of all types use devices designed to protect and back-up certain elements of the system equipment. Such devices can be found practically in all electrical installations.

Protection against damage that may result from a troubled component is performed automatically (an example is the short-circuit overcurrent protection), due to, say, an intrinsic redundancy, when a faulty element is to be replaced with one in good condition. The continuous power supply from the system that became inoperative because of damage of one or more of its elements can be restored in either of two ways.

If a system loses its efficiency fairly slowly and the functions performed by this system are of relatively minor importance, then, its efficiency can be restored and its "survivability" can be preserved in many cases through the manual control. If disturbances to normal performance of a power system are fast (fractions of a second) and the system is of high importance (power supply to large works and large populated areas), then the manual control must be supplemented by automatic control equipment performing an *emergency control.*

The concept of emergency control is associated with prevention of system-wide faults so that a failure of one element should not affect the operating conditions of other interrelated or interdependent elements.

Faults conditions in a power system usually develop in a collapse-like manner involving disturbances to the system stability, disintegration of the entire system into asynchronously operating parts, etc., which may finally lead to drastic power shortages.

As to the functions performed, the emergency control approaches the protection that covers the entire system, for which reason the emergency control equipment forms an essential part of the general system comprised by the automated dispatch control system (ADCS) facilities.

Emergency control devices appeared early in the years of creating power systems, when power plants interconnection for parallel operation called for an allowance of their interrelations and interdependence.

Excitation boost and frequency load shedding devices that appeared in the middle of the 30s should be regarded as the first devices of emergency control. One of the first 220 kV transmission lines employed devices preventing possible loss at stability of a double-circuit power transmission line, on one of the circuits disconnection. Thus, automatic facilities were used to unload the remaining circuit by rejecting some generators. Those automatic facilities were termed "VKM Interlocking" after its designer V. K. Meshkov.

Later devices were developed, both at home and abroad, to break tie-lines between two parts of a power system in case of instability and out-of-step conditions affecting the tie (known as out-of-step protection).

With the progress of interconnected power systems and complication of their interconnecting transmission circuits, the number of emergency control schemes and their types gradually grew. However, the main theory and practices of modern emergency control technique were developed in this country in the years of creating and implementing long-range transmission lines, rated for 400-500 kV, to connect the Volga hydro power plants to Moscow and the Urals. Later the emergency control schemes have been improved in the erection of thermal power plants employing power units, rated for 200-300 MW and more, with further complication of the main grid. Effective methods and facilities were developed to control power system electromechanical transients. Examples are methods like the *fast turbines control* (FTC) which consist in rapidly closing the steam control valves admitting steam to the turbines of thermal and nuclear power plants.

The emergency control schemes thus have become an efficient facility of preventing system-wide emergencies and giving significant economy.

8.2. Principles of Automatic Emergency Control

The emergency control consists of individual (self-contained) devices. It should be remembered, however, that all those devices respond to the parameters of a single electro-mechanical transient process evolving in the system and control it. The devices, therefore, become interrelated through the controlled process. We may therefore consider the emergency control as an integrated system, though certain of its apparatus perform individually. In its progress, the emergency control technology tends to overcome this disintegration of apparatus and become integrated in all respects.

With the emergency control schemes considered as an integrated system, we may say that its main purpose during disturbances of the normal operating conditions is to keep those conditions within the permissible range or get them back into the range. Comparing it with other control systems, we may draw a parallel with the modern systems of optimal control which control the motion along certain paths subject to the movement speed and energy change. The processes in power systems are rapid, and to obtain the desired results the control has to use all of its utmost means.

Attempts to optimally control electromechanical transients in power systems have revealed a specific feature of a power system. In most cases the effect caused on it by the emergency control can be of one sign only. Thus, power plant generators, for instance, can be rapidly switched off only, whereas their reconnection takes far more time, measured in minutes and sometimes in tens of minutes. The same case is with the steam turbines which are quick only in stopping steam admittance, while its readmittance takes much longer time. Such installations make a majority in electrical utilities, whereas the abilities of control actions in either direction (forcing and deforcing generators, for instance) at equal or close speeds are scarce exceptions, though fairly useful.

At the same time all methods of optimal control theory use, as a rule, alternating actions of both signs. Hence, the application of optimal control theory to the emergency control produces as yet fairly modest results. Basic concepts and techniques in this field most often employ conventional methods of analyzing electromechanical transients in power systems, i.e. stability studies and the investigation of measures to improve the stability.

The study of emergency control automatic equipment falls into several closely interrelated problems which involve the analysis of contingencies in power systems of diverse configurations, study of methods to control electromechanical transients that can be utilized at power stations and networks of different types, and also familiarization with the methods of detecting emergency situations and aids for the containment of emergencies under such circumstances. In parallel with optimal control theory the latter operation is known as *search for control strategy*, the control being any action of the emergency control on a power system.

Problems of emergency control theory are concerned with the study of stability or form part of it. However, the emergency control equipment is called upon not only to assess the stability level of a given real operating condition or conditions taken as a whole, but also to reveal measures providing the required value of this level (or a maximally possible level, if the required value cannot be achieved).

Lately many stability studies have been done with reference to the design of emergency control (structure and settings) with a view of providing control over the process.

Generally calculations of steady-state, and transient stability are carried out for substantially simplified models in which system parts are substituted by their electric, magnetic, and mechanic equivalents. This simplification is used because the process flow can be clearly traced, a method of a process control can be chosen, and emergency control automatic facilities can be properly arranged only in a model of simple configuration.

8.3. Elimination of Emergency Conditions

An equivalent most often considered in emergency control problem is a two-machine system (Fig. 8.1) comprising two generators with an interconnecting transmission system. Such a configuration can result from reducing an original circuit diagram of either a power system, or a part of a power pool separated due to its asynchronous operation (a separated part of the system is shown in Fig. 8.1 by dashed lines). A less simplified equivalent of power systems may also be used. However, even a two-machine model allows us to consider many important problems facing the emergency control, hence, we will consider it in more detail.

Depending on the power ratio between the sending and receiving ends of a power system, the circuit diagram may represent a circuit that should take into account possible variations in the generation power and demand, and also in voltage and frequency either at both ends (sending and receiving) of the transmission line, or at one, most often the sending end, of the transmission line. In the latter case the two-machine system becomes a one-machine system in the form "generator—transmission line—infinite buses".

By known quantitative methods a two-machine system having sources of commensurate power may be converted into one-machine.

The normal operating conditions of the system under consideration suffer mainly from disturbances caused by changes in the number of transmission lines that are operating at various sections, i.e. by changing the configuration of the transmission system. All components of the transmission system are operating, when all the switches shown in Fig. 8.1 are closed. If the case is that some portion of the transmission system, say, between switches *S1* and *S1'*, in the prefault state is disconnected, then such a condition is termed *outage.* Several sections of a transmission line may be under the outage condition, but this, however, should be avoided.

An emergency (abrupt) tripping of one of the transmission line sections leads to a failure known in the field of emergency control of a *failure with power surge.* This emergency situation

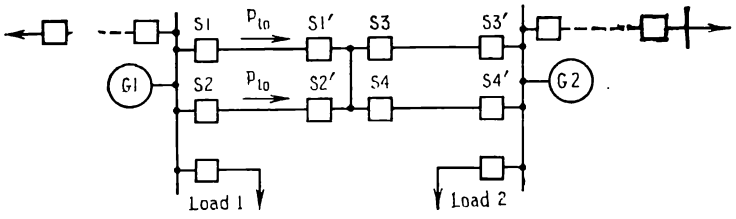


Fig. 8.1

can be readily characterized by most simple static relationships. Thus, for instance, if the power of each circuit under the initial conditions is P_0, then, after a circuit of any section of the transmission system has been disconnected, the parallel circuit will carry a load approximating $2P_0$. If this value is above the steady-state stability limit of the transmission line under post-fault conditions, the further normal operation of the line becomes impossible.

A similar situation may arise during switching off a heavy load (Load *1*) at the sending end of the transmission line (see Fig. 8.1) or when a power shortage occurs in the receiving system.

The choice of the structure and settings of emergency control schemes starts with an analysis of similar static relations.

The phenomenon so far considered in this text, however, represents an intricate transient process during which the generator rotors gain kinetic energy. In view of this, the analysis of static relations forms only the first stage of complex work.

The general approach to liquidating emergency situations consists in operations correcting the equilibrium between the mechanical (P_m) and electrical power (P_e). At the sending end of the transmission system this balance must be changed in favour of the electrical (decelerating) power and at the receiving end—in favour of the mechanical (accelerating) power. Facilities and techniques that influence this balance are dependent on the type of power plants and a series of other factors.

The only measure of changing the power balance at the sending end was represented for a long period of time by tripping some generators of the power plants practically at once with the aid of automatic devices made for the purpose. At hydro electric power plants this provision remains the principal one till now, and it has been shown by experience that this is not only effective, but also relatively harmless to the equipment. Generation tripping sometimes is used at thermal power plants. With new modern power units, however, this method cannot be believed fully harmless and is now replaced by fast turbine control, i.e. by rapid reduction of steam admission to the turbine effected either by closing the steam intercept valves, or (which is more efficient) by actuating the steam control valves

through special electrohydraulic converters inserted into the control systems of turbines.

An effect on the turbine control system makes it possible to set more accurate steady-state relations under post-fault conditions without resort to coarse stepwise changes in these relations featured by the generation rejection method.

At the receiving end of a transmission system the principal method of dealing with the power balance is by switching out certain loads which in principle can be accomplished instantaneously.

Combining the generation rejection method at the sending end with the load shedding action at the receiving end forms the so-called *balance control* fairly efficient in most of intricate power systems.

Recently wide use is found by special load-shedding automatic devices serving large consumers which allow short-time interruptions in the power supply.

The above-mentioned capabilities cannot be utilized in all events. If the sending part of the system is far more powerful than the receiving part, then, proceeding from the necessity of sustaining the power balance in each of the system parts with a limited transmission capability of the link between their parts (reduced under emergency conditions), it would be necessary either disconnect a large number of generators in order to reduce the frequency in the entire pool, or allow the system to be separated into islands, the power balance in its receiving portion being restored through the automatic frequency load shedding (AFLS). This method is often used in modern power systems, an increase in the frequency caused by AFLS being utilized to facilitate resynchronization (if the transmission has been operating under asynchronous conditions without its separation).

Rapid loading the units may be a rather effective facility of restoring the balance of power in the receiving part. To this end, however, there must be present at least two factors: enough power available at the receiving part units and a possibility of utilizing this power quickly, i.e. a possibility of rapid loading.

Considering processes associated with a power shortage, one should remember that the restoration of power balance is much assisted by a phenomenon known as "self-unloading", e.g. a drop in the load power occurs when the frequency is decreased. As is known, the value of such a self-unloading can be roughly assessed as 2% of power per 1% of frequency. Therefore, a 1.0 to 1.25 Hz decrease in the frequency, that does not cause AFLS operation, reduces an imbalance by 4-5% of the full load power of the receiving part of the system. More than that, in presence of spinning power reserve (including the reserve due to opening the overload valves), the load is also gained under control of the speed governors. This process is somewhat slower, than the self-unloading process and takes several seconds. Nevertheless, its effect is well perceptible.

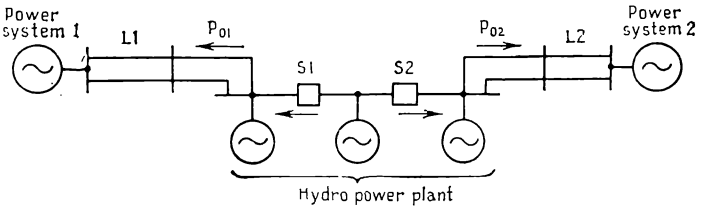


Fig. 8.2

In this connection a unique method of eliminating emergency conditions like those above that is pioneered in the USSR and later used in other countries is of great importance. Under this method the transmission network continues its operation after an asynchronous condition has occurred, waiting for "spontaneous" resynchronization. This will take place after the operation of the receiving and sending end speed governors reduces the frequency difference to a value at which the exporting and importing parts of the system become pulled into synchronism.

In this case an emergency condition usually lasts from several seconds to several tens of seconds and is eliminated without special efforts of attending personnel and particular automatic devices. The resynchronization in this event may be assisted by AFLS, whilst the load disconnected by it is picked up by the frequency autoreclosing action.

Of course the use of the above method is advisable only under particular conditions known as resynchronization. If the resynchronization conditions are not satisfied, an emergency shortage of power may be remedied by other measures.

One of such measures is illustrated in Fig. 8.2 showing a large hydro electric power plant located between two power systems *1* and *2*. Separating this power plant under a shortage of power into islands (at switch *S1*) may preserve the transmission operation, though weakened by disconnecting one of its circuits, but useful as to the reduction of imbalance (a power shortage in the receiving system). Referring to the figure, in this case different quantitative relations may appear and it may be necessary to trip an additional part of generation or the like measures as dictated by the direction of flow and value of the power at the separation point (switch *S1*). The separation may be accomplished not only on the power plant busbars, but in the network adjacent to it. The automatic equipment performing such a separation is often called *out-of-step protection.*

When tripping some sections of transmission lines affects their transmission capability, use is made of techniques for short-time compensation for a decrease in capacity. This method may be

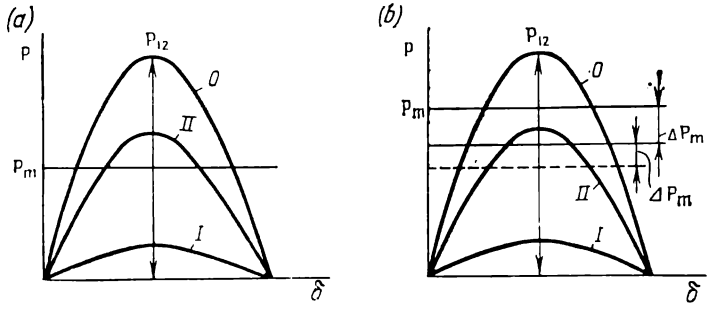


Fig. 8.3

applied only to transmission lines furnished with series-capacitive compensation (SCC). This consists in switching out a part of capacitor banks operating in parallel. As a result the capacitive impedance x_C is increased, while the transfer impedance equal to the difference between the inductive reactance x_L of the line and x_C decreases. It is evident, that each remaining bank of capacitors carries an increased current, for which reason the duration of such a condition, called *SCC forcing* is usually measured in seconds or tens of seconds. As to increasing the transmission capability under the after-fault conditions, the effect of the SCC forcing is not too much. Nevertheless, it may come out, that this effect and the overpower transfer time (seconds) will be enough for the speed governors action at the receiving part of the system and will exclude or diminish the necessity of load shedding through the AFLS.

Therefore, the analysis of static relations under the considered or similar contingencies in a power system may tell us much about the methods of eliminating emergence conditions.

It is proposed to consider now the dynamics of processes developing after the above disturbances. Figure 8.3*a*, *b* gives two power angle curves of transmission system. First of these shows the characteristics of the initial condition (curve *O*), short-circuit condition (curve *I*), and post-fault condition—curve *II* whose amplitude P_{12}^{II} exceeds the value of mechanical power P_m applied to the generation units under the initial conditions, i.e. this meets the steady-state stability requirements under the post-fault conditions.

The other diagram shows the case when P_{12}^{II} is less than P_m and the conditions of post-fault steady-state stability are not satisfied. The conditions can be restored say by reducing the mechanical power for the value of ΔP_m through generation rejection (GR) and fast turbines control (FTC). In either case, however, an acceleration area is formed which is characteristic of eccessive kinetic

energy stored in the rotors of the generation units. In order to meet the transient stability conditions, this energy stored in them during the transient (fault) must be killed.

No deceleration area is present in the diagram shown in Fig. 8.3*b* and it must be created artificially. The most simple way to do this is by increasing ΔP_m through rejecting a bit greater generating power in generation rejection (dashed line) or through obtaining a greater droop in the case of FTC. This way, however, is not most effective at all times. The other method of later practice is by connecting to the power plant busbars special breaking resistors for a short period of time.

This method is usually termed *electric* or *electro-dynamic braking* (EB). Its drawback is in extra costs of EB equipment: resistors and their switches that are designed to handle only resistive loads and unlike the conventional breakers are often called *contactors*. In addition, load resistors and contactors are difficult to satisfy their reliability requirements.

Investigations on emergency last turbines control have yielded a new and most effective method of challenging the problem under consideration. This consists in that the turbine mechanical power is reduced at first to a droop far greater than is dictated by the steady-state relations or steady-state stability conditions. A shortage of mechanical power formed in the sending portion of the system decelerates the generators with resultant rapid killing of their excessive kinetic energy. This done, the power output of the turbines is gradually increased to a value meeting steady-state post-emergency conditions. These are controlled by means of electro-hydraulic converters.

This method is usable only at steam power plants. Methods are developed, however, for quick dewatering of the turbine scroll casings and reduction of the vacuum in the draw-off tubes, which produce an effect very close to that of the emergency control of steam turbines.

With the dynamics of the above processes under consideration, one cannot disregard the effect of the excitation system of the generators and the apparatus that control it—excitation forcing devices and voltage regulators (sometimes, these are considered as a whole).

The excitation forcing opens the way to upholding the voltage across the generators terminals under emergency conditions and sometimes even to a small increase in the voltage during its restoration in order to add 5-10% to the post-emergency margin of the transmitted power. Certainly, this may be done only for short time and with great care to avoid the operation of the overvoltage protection or perhaps an insulation puncture.

Voltage regulators, in particular, if these regulators are of a forced control type, dampen the arisen oscillations facilitating the return of the system to a new steady-state condition. In certain cases this

damping action is recommended to be effected with the aid of FTC as well. To this end, however, the opening and closing speeds of the turbine valves should commensurate with each other.

Automatic reclosing operation is of greater importance, when used on power transmission lines. Thus, in case of instable failure, the automatic reclosing action allows the duration of a forced deficit of power in the receiving system to be reduced (especially, when the turbine control is used for power containment in transmission weakening), line interruption time in a three-phase autoreclosing being cut down to several seconds. In this time circuit breakers cut off power supply of some part of the system. After a successful reclosure of the disconnected section, however, the automatic control of the turbines may remove the containment and the frequency-actuated auto-reclosing will "pick up" the shedded load.

The rapid reclosing allows an interruption in the transmission operation to be shortened to fractions of a second, while the one-phase auto-reclosing reduces the value the transmitted power is reduced under emergency conditions.

Upon the consideration of emergency conditions with a power surge in the two-machine scheme of a power system, a conclusion may be made that this fault would be of a cascading type typical of system failures, if there were not present an emergency control scheme. Suppose, for instance, that the receiving system would import as little as 30% of its required power. An islanding of this system because of power surge, if the steady-state stability conditions are not met (see Fig. 3.8*b*), would lead to a 30% deficit of power in the receiving system. In order to compensate for this, the frequency would be reduced by 7-8 Hz. At such a frequency, the circulation pumps could not supply sufficient amount of water to the boilers and the result would be an inevitable outage of many power plants. Therefore, the initial amount of power deficit would be materially increased and the power supply to the consumers could be ceased almost completely.

The various kinds of emergency control equipment make it possible to greatly reduce the severity of faults and in certain cases to fully exclude the AFLS action, a small imbalance in that being compensated for by selfunloading of the consumers.

A two-machine scheme is an example of a power pool in which the emergency control facilities allow you to obtain the above-mentioned effect. This scheme, however, does not cover the entire variety of configurations encountered in power systems. Often encountered are diverse three-machine and ring networks and other types of power pools. Normal operation of such power pools is difficult to be restored without changing their configuration. In view of this, the systems are usually sectioned into more simple, specifically into two-machine schemes.

When a fault occurs under normal operating conditions of a power system a series of certain measures are taken and carried out automatically. These measures involve such devices as circuit breakers, turbine governors, voltage regulators, and the like which perform the functions of actuators. In addition, use is made of automatic devices that send control pulses to the actuators, many such devices being used to control concurrently several actuators and perform a number of functions.

8.4. Structure of Automatic Emergency Control

A block diagram given in Fig. 8.4 illustrates in a pictorial manner interrelations of certain emergency control devices and of the functions they perform.

In the diagram the entire emergency control is conventionally divided into two parts—special and general. The special emergency control equipment is installed in power system only when its use is justified by a preliminary analysis of emergency situations and corresponding calculations. The use of general emergency control automatic equipment in the Soviet power systems is compulsory, though special calculations are required in this case as well.

The top portion of the diagram lists a set of problems to be solved in case of emergency conditions of power systems in order to prevent further expanding of the failures. The next row shows emergency control schemes proper.

Next are listed measures (actions) carried out on control signals from the associated schemes to accomplish functions assigned to them. The bottom row of the diagram shows the technical facilities (actuators) by means of which the measures in question are carried out.

Let us consider the structure in somewhat more detail. The essential functions of the special automatic controls are functions associated with the provision of steady-state and transient stability of a power system. The basic measures taken in this case have been considered above. An additional mention should be made here of tripping shunt reactors which increases the amplitude of power angle curve with an effect similar to that of forced SCC, prevention of out-of-step operation when it is intolerable, and also of ceasing out-of-step running when its duration exceeds the specified limits.

If a part of a power system affected by an excess of power includes both hydro power plants and thermal power plants, one has to take into account the slow performance of the hydro power plant governors. As a result, the frequency under excessive power conditions may increase by 10-20% and more. These values are not dangerous to hydro turbines, but are intolerable where steam turbines are utilized (a danger arises to the turbine blades). In view of this, special meas-

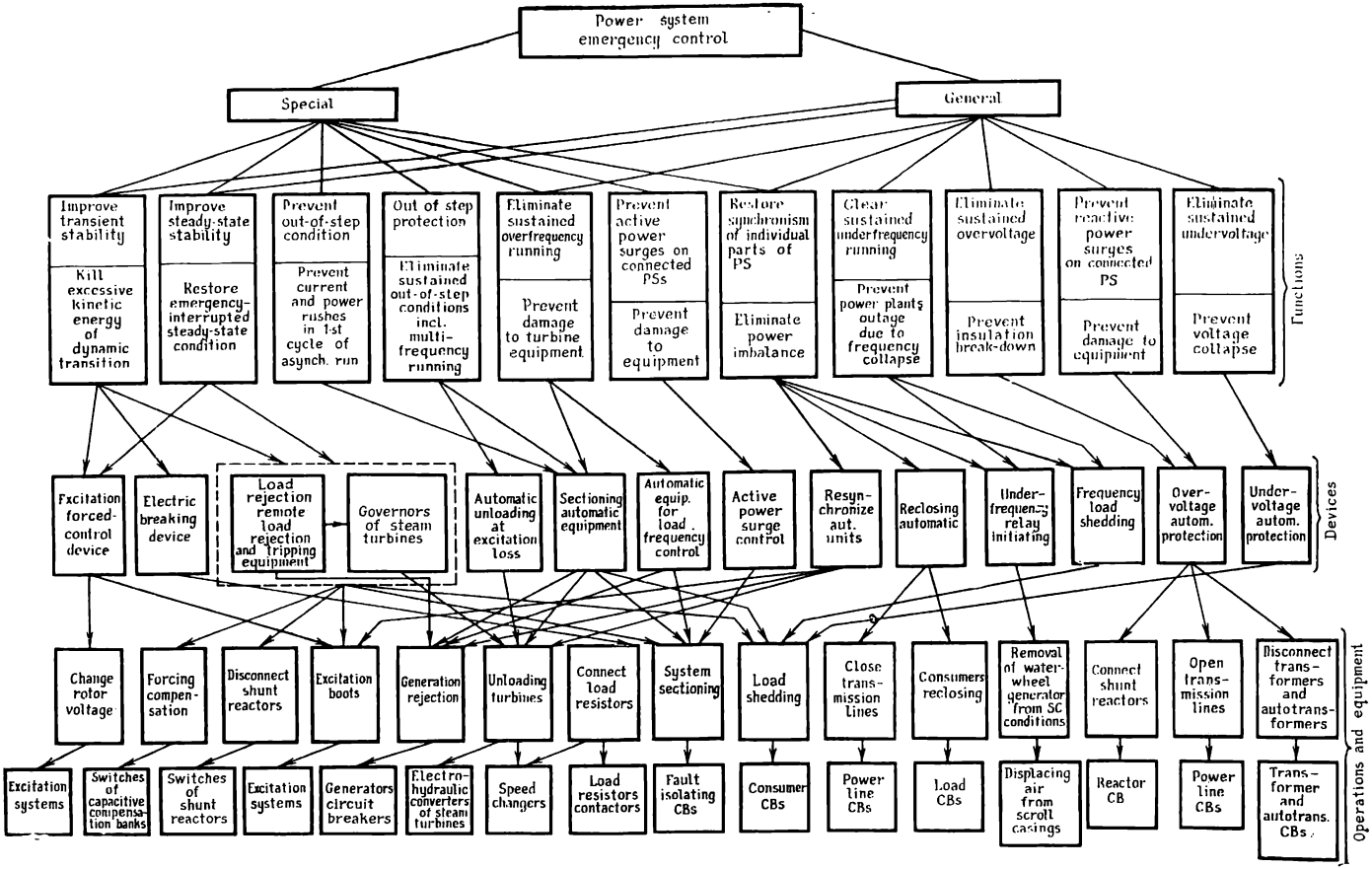

Power system emergency control
Special
General
Improve transient stability
Kill excessive kinetic energy of dynamic transition
Improve steady-state stability
Restore emergency-interrupted steady-state condition
Prevent out-of-step condition
Prevent current and power rushes in 1-st cycle of asynch. run
Out of step protection
Eliminate sustained out-of-step conditions incl. multi-frequency running
Eliminate sustained overfrequency running
Prevent damage to turbine equipment
Prevent active power surges on connected PSs
Prevent damage to equipment
Restore synchronism of individual parts of PS
Eliminate power imbalance
Clear sustained underfrequency running
Prevent power plants outage due to frequency collapse
Eliminate sustained overvoltage
Prevent insulation break-down
Prevent reactive power surges on connected PS
Prevent damage to equipment
Eliminate sustained undervoltage
Prevent voltage collapse
Functions
Excitation forced-control device
Electric breaking device
Load rejection remote load rejection and tripping equipment
Governors of steam turbines
Automatic unloading at excitation loss
Sectioning automatic equipment
Automatic equip. for load . frequency control
Active power surge control
Resyn-chronize aut. units
Reclosing automatic
Under-frequency relay initiating
Frequency load shedding
Over-voltage autom. protection
Under-voltage autom. protection
Devices
Change rotor voltage
Forcing compen-sation
Disconnect shunt reactors
Excitation boots
Generation rejection
Unloading turbines
Connect load resistors
System sectioning
Load shedding
Close trans-mission lines
Consumers reclosing
Removal of water-wheel generator from SC conditions
Connect shunt reactors
Open trans-mission lines
Disconnect trans-formers and autotrans-formers
Excitation systems
Switches of capacitive compensa-tion banks
Switches of shunt reactors
Excitation systems
Generators circuit breakers
Electro-hydraulic converters of steam turbines
Speed changers
Load resistors contactors
Fault isolating CBs
Consumer CBs
Power line CBs
Load CBs
Displacing air from scroll casings
Reactor CB
Power line CBs
Trans-former and autotrans. CBs
Operations and equipment

Fig. 8.4

ures are to be taken to separate the power system into parts utilizing hydro power plants and steam power plants.

Besides, cases are possible when a small local system is connected by a tie-line to the busbars of a powerful hydro power plant together with a trunk transmission line. If that is the case, an open circuit in the trunk transmission line will lead not only to an increase in the frequency, but also to an associated overload (power surge) of the mentioned tie-line and other elements of the local system. Therefore, specific protective measures are to be taken in this case too. Referring to Fig. 8.4, a group of specific functions is performed mainly by islanding the system in order to equalize the power balances through certain actions performed on the generation units and load.

Sectioning a system and out-of-step running of its separated parts should involve restoration of synchronism. To this end, resynchronization conditions must be provided first of all, e.g. the frequencies of the corresponding parts of the system must be brought close to each other (by means of, say, changing the power balance of the parts involved) and, if necessary, the circuit breaker (CB) that has been open in the sectioning operation must be reclosed.

The latter two cases are related mainly to those events when changes in the system balance result in substantial deviations from the permissible operating conditions in frequency or voltage. Such deviations of rather high values that last for a certain period of time may cause damage to the equipment and collapse of frequency and voltage. As is known, a collapse of voltage is caused by reversal of induction motors and a collapse of frequency, by forced shutdown of steam plant generation units due to a drop in the capacity of their auxiliaries.

It is this group of automatic control devices that deals with the removal of such a risk. In this event, such actions are of importance as frequency-actuated start of hydro plant generators (their switching over to generation mode of operation from the SC operation which automatically takes place when the frequency drops) and a series of actions to disconnect and reconnect shunt reactors, autotransformers, etc.

Under the risk of real insulation puncture, extreme measures are to be taken, i.e. opening of the transmission lines.

Such are in general the functions of the emergency control automatic facilities and techniques of their performance. Their elaborate study can be achieved through a thorough analysis of the block diagram with regard to all that has been discussed above of the two-machine scheme of a power system.

The advanced modern emergency control, as follows from its structure, monitors the operating conditions of a system and has an effect on them, regarding all necessary parameters. More than that, the corrective actions continue until the said parameters are within

the permissible range of values. It is this circumstance that bears out the statement that the emergency control is a facility of preventing the system operating conditions from coming beyond the permissible range and returning them to this over a permissible trajectory, if we cannot prevent such an event.

8.5. Emergency Situations and Requirements for Emergency Control

One of the most important tasks of emergency control theory consists in an analysis of emergency situation (contingencies) in the power system and working out the requirements for control schemes and actions aimed to prevent instability and to restore normal operating conditions. Such an analysis is based on the stability of the power systems operating in parallel. The calculations are made with the aid of digital and analog computers, a.c. network analyses or electrodynamic (physical) models. These calculations have specific features in which they differ from the calculations made to determine the stability level of a power system.

The first of these specific features consists in that the calculations made specially take into account various emergency control actions which are analyzed in planned versions. However, design calculations of a complete network are suitable, but little, for the analysis of the emergency control property, because the system intricacy renders these calculations less clear. Therefore, the other specific feature consists in that the ordinary type stability calculations are, as a rule, preceded, accompanied and terminated by an analysis of simplified models in which the processes occurring in the system and the effect of the emergency control facilities on them manifest itself most clearly.

The most popular simplified model is a model of a two-machine power system, special case of which is a network of the type "machine—line—system of infinite power". Sometimes, analyses are made of three-machine power systems and networks with more machines (five or eight). Peculiarities of emergency situations in such models and the know-how to handle them when use is made of emergency control facilities are set forth below in a condensed form. A typical diagram for the purpose will be the diagram of a two-circuit transmission line shown in Fig. 8.1.

Emergency situations in a two-machine system. This system is fairly suitable for analysis, since its model may be readily replaced, as you know, with a one-machine model after calculating steady-state relations and proceeding to the analysis of transient conditions. Note, however, that this replacement is possible only for relative movement of the system, i.e. the motion of the rotor of generation

unit *G1* with respect to *G2* defined by the time power angle $\delta_{12}(t) = \delta_1(t) - \delta_2(t)$.

With the system translational motion evaluated in terms of the system mean frequency to be assessed, both machines should be treated as a whole.

Analysis simplification and clearness improvement resulting from the replacement of a two-machine model with a one-machine system are especially useful when such a replacement is made on system having 330-500 kV transmission lines in which losses are small. If that is the case, the losses are neglected, the loss angle being taken as $\alpha_{12} = 0$. Besides, the power plant bus voltage is considered constant. This may be achieved, for instance, by performance of forced control voltage regulators. Note that such an assumption is not true at the instant of short-circuit, but is true under the post-fault conditions.

With the above-mentioned assumptions duly allowed for and the inherent-regulation capabilities (asynchronous torque, load frequency response, etc.) neglected, the swing equation of a given system may be written as follows:

$$(\tau_{j,\text{eq}}/\omega_s)(d^2\delta_{12}/dt^2) + P_{12}\sin\delta_{12} = \Delta P \tag{8.1}$$

where

$$\tau_{j,\text{eq}} = \tau_{j1}\tau_{j2}/(\tau_{j1} + \tau_{j2}) \tag{8.2}$$

$$\Delta P = \frac{P_{c1} - P_{m1}}{\tau_{j1} + \tau_{j2}}\tau_{j2} - \frac{P_{c2} - P_{m2}}{\tau_{j1} + \tau_{j2}}\tau_{j1} \tag{8.3}$$

In these equations P_{12} is the amplitude of the power angle curve of the transmission system; τ_{j1} and τ_{j2}, acceleration time of the units; ω_s is a synchronous speed; P_{m1} and P_{m2} are total mechanical powers of the prime movers of the first and second power plants (equivalent power units); P_{c1} and P_{c2} are consumer powers at the stations buses.

A set of equations is thus created less rigorous than is generally used in the theory of power systems stability but much more clear. Assisted by this set of equations, one can assess the dynamic relations in most typical emergency situations: weak transmission (circuit disconnection in one of double-circuit sections of a power transmission line), deficit of power in the receiving system and excessive power in the sending system.

It is good practice to start the consideration with the latter case as most pictorial.

Excessive power in the sending portion of a system. This emergency condition may be represented as disconnection of a feeder from the power plant to supply power to a powerful local consumer. Let this disconnection be the result of a very distant short-circuit, in this

case the power plant suffers only from a change in the active power without changes in the voltage.

Let the pre-fault power delivered to the local consumer be P_c which together with the trunk line load P_l add up to the power plant output $P_g = P_c + P_l$. Proceeding from the steady-state relations, one could expect that after the disconnection of the load, the transmission line power would grow to the value of P_g because of a power surge on the line equal to P_c. However, it would be unfair to expect such a load directly at the instant of disconnection. This will not occur and in the simplified model of a two-machine system in which the generator internal reactance x_g is neglected, the line load at first will exactly equal P_l. A power surge will take place under the transient conditions, when an imbalance (excessive power) equal to P_c appears on the generators shaft of the sending part of the system and the rotors of the generators will start accelerating first at a rate equal to $\omega_s P_c/\tau_{j1}$. As this happens, the angle δ_{12} will start its increase and the transmission line will start picking up load. In this case, the system will be under the usual conditions of steady-state and transient stability which can be satisfied depending on the system parameters and amount of disturbance. In particular, three cases may be considered:

(1) Both conditions of stability (steady-state and transient) are satisfied. In this case, the transition is stable and involves a slight increase in the system frequency. The frequency governors will correct this increase by limiting it to the value Δf which can be defined as $P_c\sigma$, where σ is the system static frequency slope referred to the same base power as P_c.

(2) The steady-state stability conditions are met (P_m is less than P_{12}), but the transient stability conditions are not satisfied. This situation can be assessed by the following approximate formula:

$$P_c \leqslant 0.75\,(P_{12} - P_m) \tag{8.4}$$

If this inequality is not satisfied, then the transient stability conditions are not met and measures should be taken to quickly kill the excessive kinetic energy stored by the rotors of the generation units during the transition time.

(3) Neither transient stability, nor steady-state stability conditions are satisfied. If that is the case, the kinetic energy killing solely is obviously not enough and measures should be taken to restore the steady-state stability conditions. To this end, under the post-fault conditions, after the excessive kinetic energy has been killed, the condition: $P_m < k_s P_{12}$ should be satisfied, where k_s is a safety factor defined from the standard requirements for the steady-state stability margin under the post-emergency conditions. Prior to intervening of personnel, the value of k_s is generally taken in the USSR as equal to 0.92. This value, however, may be corrected

according to the actual situation in the system and possible effects of the automatic control on the process.

In this and the like cases, the operation on restoring the steady-state stability conditions is called *unloading of transmission line* (power plant, utility). It will be shown later that such unloading can sometimes kill excessive kinetic energy too. Strictly speaking, however, these two operations should be separated from each other.

Deficit of power in the receiving part of the system. This deficit of power results from disconnecting a large generation source in the system part under consideration, of from opening the trunk transmission line connecting this part to another source of generation. In the latter case, a change over from a three-machine system to a two-machine system takes place.

Referring to the swing equation (8.1), one can easily ascertain that the shortage of generation power in the receiving part of the system, as to the relative motion, is similar to the power (load) rise in the sending part of the system. The physical processes, however, will be other. In fact, under given emergency conditions, the power angle increases because of deceleration in generation units *G2*, rather than due to acceleration in generation units *G1*, and the translational motion speed (the system mean frequency) will decrease, rather than increase.

In that, the nature of stability conditions and protection actions will be the same. Note, however, that the transient stability may be preserved only when the decelerating action in the system receiving part is rapidly discontinued, i.e. the power balance is restored in it. With no regard to load shedding, this restoration will take place mainly due to the self-unloading of the consumers, i.e. due to a decrease in the frequency. Inasmuch as the frequencies in both parts, as is evident, must be equal, there are only two possibilities of achieving it: you have either to reduce the frequency in the sending part of the system, or separate the system at the sending end so as to provide some power for the trunk line under consideration. This problem has been adequately considered above. Note only, that at this point, as in the above case, by the term "power surge on the transmission line" is meant a gradual change (increase) in the load carried by the sending part generators of the system with an increase in the power angle caused by the deceleration in the generator units of the receiving part.

Emergency conditions involving changes (weakening) in the transmission line diagram. Most often such emergency conditions arise as a consequence of a short-circuit in some section of the transmission line and sometimes in its absence (an example is a malfunction of the protection equipment or personnel). In this case, therefore, special emphases should be laid on a complex dynamic transition defined quantitatively by the prefault operating conditions and a

maximum of the power angle curve of transmission line P^0_{12}, short-circuit conditions with a maximum of P^I_{12} and post-emergency conditions with a maximum of P^{II}_{12}. As is known, the actual values of these magnitudes are dependent on the transmission line parameters, kind of fault, etc. Despite this, a survey of many transmission lines made it possible to obtain certain data on the relations typical of such emergency conditions. Thus, if $P^0_{12} = 1$, then under the emergency conditions in question (a two-phase fault to ground), the value of $P^I_{12} = 0.2$ to 0.25 and $P^{II}_{12} = 0.8$ to 0.75.

With a standard stability margin of 20%, the value of the line initial power $P_l = 0.83$ (it is not equal to 0.8, as in the formula used to determine the steady-state stability margin, the difference $P^0_{12} - P_l$ has been referred to P_l rather than to P^0_{12}). From this, it follows that, when the transmission line load approximates the maximum standard, opening the circuit at one of the sections disturbs both the transient and steady-state conditions.

As this happens, the nature of the dynamic transition is determined by two absolute motions, namely: the generators of the sending part suffer from an excess of power and accelerate, while the receiving system looses some power and decelerates. The sum of these motions leads to a gradual increase in the relationship angle σ_{12} and the growth of load in the transmission circuit, remaining in operation, which at first suffers no changes.

Therefore, despite an instantaneous change in the steady-state relations, no instantaneous power surge occurs here either. In fact an instantaneous power drop takes place on generators *G1* (because of the growth in the transmission line impedance).

A complicated dynamic transition occurring in this event differs from the considered simple transitions in that it has a relatively large acceleration area which affects the upkeep of the transient stability of the transmission line.

A power deficit in the receiving system forms the principal feature of the power balance turned out under post-emergency conditions. The reason for this is evident. It is a decrease in the power flow to the receiving system over the transmission line. This deficit of power can be compensated for with the contemporary facilities only on account of the considered decrease of frequency. This feature of a given transition manifests itself the stronger, the greater part of the power consumed in the receiving system is covered by the power sent to it over the trunk transmission line.

If this part of the power is great, situations may arise in which to restore the normal operation one has to resort to sectioning the sending system, a variant of such sectioning consists in separating specific generation units for a work only into the line under consideration. If that is the case, a very heavy disturbance to the normal operating conditions of the receiving system may occur (in particular,

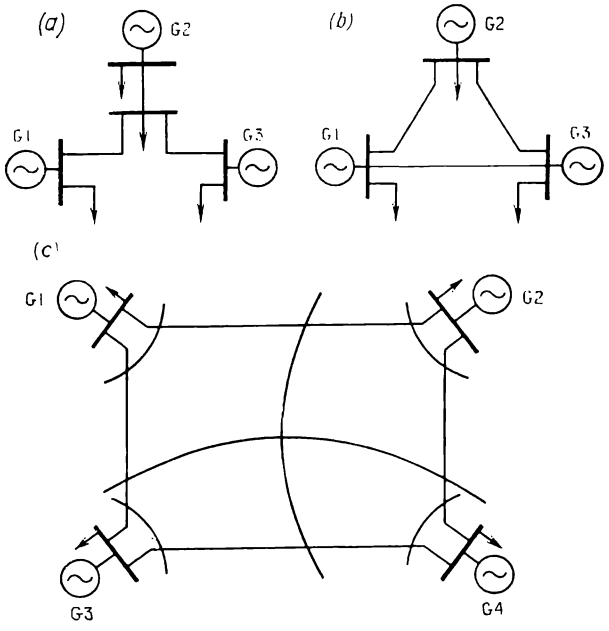


Fig. 8.5

the receiving system may loose all the power, rather than part of P_t transmitted over the disconnected section). Therefore, development of methods for instantaneous load shedding in the receiving system known as *unloading of receiving system* is of importance.

Emergency situations in multimachine systems. When working with emergency control schemes, multimachine systems have to be considered in addition to one- and two-machine systems.

The essential features of a multimachine network can be considered using a three-machine model system (Fig. 8-5*a*, *b*). It may be of diverse configurations. Examples are star and delta configurations. Often one can find ring networks comprised by four, five or more generation power plants (Fig. 8-5*c*).

Phenomena and processes occurring in these networks are far more complicated, and in this case it is not so easy to obtain as vivid a representation of them, as the case was with the two-machine system. In their physical nature, however, they approximate the above-considered schemes, for which reason, only the essentials of an analysis of multimachine networks will be discussed.

Dangerous network cross-section. A ring circuit comprised by four generation power plants is shown in Fig. 8.5*c*. Considering the steady-state relations in this circuit, one can see that disconnection of one line of the ring will result in a power surge on the tie-lines remaining

in the operation. In this case, the risk of the stability loss is dependent on the sum of powers flowing under the pre-fault conditions over the transmission lines enveloped by arcs in the diagram. These arcs represent certain network cross-section of the ring for which the heaviest (as to the stability) conditions should be found by calculations. This section is known as a dangerous cross-section (sections). With this point determined, the required steady-state relations can be comparatively readily revealed, i.e. the load carrying capacity of the found section under the post-emergency conditions and also the required level of generation rejection at the ring power plants in order to reduce the power flow (transfer) through the dangerous sections to a tolerable value.

To determine the level of generation rejection on a power plant according to this condition, one has to calculate the power flow branching and also select system points at which load rejection must be accomplished, since several power plants may be subject to unloading. This problem can be analyzed and solved with ease.

Actions to kill excessive kinetic energy are determined with more difficulty. With a ring network, an exact determination of this kind is very laborious and often, to save time and effort, the transient stability is provided through main tie-line unloading of higher level than is dictated by the steady-state stability conditions.

Multifrequency asynchronous operation. Another specific feature of a multimachine system is the so-called *multifrequency asynchronous operation.* As an example consider this phenomenon on a star-connected three-machine diagram. Comparing this diagram with the two-machine one, two angular frequencies (ω_1 and ω_2) of generator unit rotation and one slip value (s_{12}) proportional to their difference can be seen in the two-machine system under disturbances, while three rotational speeds (ω_1, ω_2, ω_3) and three slips (s_{12}, s_{23}, s_{31}) may be within a three-machine system.

Asynchronous operation with several different slips between different generators is known as *multifrequency asynchronous operation.* System emergencies occurring in complicated power systems often involve such multifrequency operation. This condition is dangerous in that attempts to restore the synchronous operation without partitioning the system under customary conditions turn out to be practically ineffective and their continuation leads to an increase in the time of asynchronous run which is not always tolerable.

This circumstance is taken into consideration by modern practice. Thus, all points of complicated power system that may suffer from stability loss are furnished with out-of-step protection operating in such a way that ties are preserved between not more than two equivalent generators in the system.

In this manner a multimachine scheme is converted into a number of two-machine schemes in which asynchronous operation is easy to be terminated.

One of the causes of multifrequency asynchronous running may be a phenomenon of electromechanical resonance.

Electromechanical resonance. This is a fairly complex phenomenon occurring in multi-machine circuits (starting with a three-machine network). It is very dangerous.

For a long period of time the nonlinear nature of the swing equation hindered with the establishment of quantitative relationships accounting for possible onset of electromechanical resonance. Today these relationships are found. In this publication, however, they will be considered only qualitatively.

Refer to Fig. 8-5*a* depicting a star-connected three-machine network. Let to some reason the generators *G1* and *G2* run out-of-step with each other, while the generator *G3* continues its running in synchronism with the generator *G2*. As this happens, the nodal point voltage of the system and power flows and the like oscillate periodically at a frequency determined by the value of slip s_{12}. It is clear enough that the oscillation frequency Ω will be close to the natural resonant frequency of the equivalent generator *G3* with due regard to its coupling with the system. Under certain conditions the oscillations at the frequency Ω can cause "hunting" of this generator so that it looses its stability with resultant multifrequency asynchronous operation. As it was mentioned, this condition can be terminated only by sectioning the system.

Therefore, emergency situations arising in a complicated power system are in many instances similar to the situation encountered in a two-machine system. In that, a point to be noted is that the system sectioning may result in whatever different values of power balance as dictated by the value and direction of the power flow in the cross-sections under pre-fault conditions. To illustrate this, consider a simple diagram shown in Fig. 8.2. Suppose there is a deficit of power. If that is the case, the power plant may be sectioned at two points, switches *S1* and *S2*. Power flow directions shown in the diagram indicate that when sectioning is on the switch *S1*, tied with power system *1* is the power plant part under power deficit with all aftereffects resulting from this situation. When switch *S2* is open, this part of the power plant will carry excessive power. Therefore, the analysis of power flows in possible sectioning points under prior-to-emergency conditions is one of the most essential components of the general analysis of emergency situations during the emergency control design.

Requirements for emergency control schemes. Analyzing emergency situations in power system of any configuration, revealing the risk to their stability and other factors involving the action of emergency

control schemes, and also determining the kind, point of application, and intensity of this action always involve a certain number of variables which can be treated as a certain multidimensional vector **B**. Components of this vector will be always the system state variables **S** that have the form of the parameters of its circuit S'' and operating conditions S', and, if necessary, of disturbance v and control u, too.

Inasmuch as analyses are generally made on a collection of operating conditions and diagrams, multidimensional areas are formed which, depending on their structure and dimensions of the spaces used, may be of different sense. Thus, for example, the following areas may be classified separately: a stability area in the space of system state variables, when studying the stability; an area of permissible current loads carried by the lines, when investigating the power flow; and an area of permissible voltages, when analysing the system voltage profile on the nodal points of a system, etc.

Most important are, however, areas generalizing all these variables and combining them with disturbances control variables.

Let S_0 be an area of the pre-fault conditions of a system and S_2 be an area of its post-emergency conditions. Next, separate subarea S_{2p} out of area S_2 and call it permissible. Indicate also the existence of return area S_r contained in S_2 through which the system returns, when it is beyond the subarea S_{2p}.

The system obviously should be in the area S_r only at the final time t_r. Herein, a permissible subarea $S_{r.p.}$ must also be separated, and time (say, the duration of asynchronous operation t_{as}) may become one of the parameters regulated by this subarea. Having introduced v and u, we obtain conditions

$$\left.\begin{aligned} &uv\,(S_0) = S_2 \subset S_{2p} \\ &u \subset U,\ v \subset V,\ S_r \subset S_{r.p.} \end{aligned}\right\} \tag{8.5}$$

which couple the problems of selecting post-emergency control facilities and planning the operating conditions of the power system. In that, the more effective these facilities, the wider the area of initial operating conditions that can be accepted in such planning, i.e. the better the possibility of satisfying the requirements for the economical efficiency of power systems, and quality of power supply with no risk of reducing the stability level.

In order to provide the above effect, the automatic equipment should possess certain capabilities, i.e. meet certain requirements. In this event, these requirements are generally divided into *requirements to the impact on power system* and *requirements to apparatus*, the former following directly from the analysis of emergency situation in power systems being a basis to obtain the latter requirements directly concerning practical use of devices. Such a division is permanent, as it reflects two stages of design work following each

other, the work sometimes being carried out by two different groups of specialists—power system experts and electronic engineers.

As early as in the first stage of design work, however, it should be kept in mind that the most important requirement to the emergency control apparatus covers its reliability and, therefore, simplicity. This requirement will be met, if that minimum of features, that are compulsory, is specified in drawing out the requirements concerning the power system operations. At the same time, it is good practice to specify those qualities of emergency control which allow the transient process to be favourable and improve the control service and other features. To this end, in discussing the system operation requirements placed on the emergency control, all its quality features are divided into compulsory and desirable which are listed in comparison.

Compulsory Quality Features	**Desirable Quality Features**
Effectiveness—a capability of holding the system within the permissible area of returning it back to this area along a trajectory that preserves the system equipment and maintains the continuity of power supply to the consumers.	*Optimality*—a capability of holding the system within the permissible area or returning it back to this area along a trajectory bringing a minimum or a maximum to a certain functional associated with the performance of the system or its essential components.
Accuracy—a capability of selecting the intensity of actions not in excess of a maximum permissible value.	*Minimum intensity*—a capability of limiting the intensity of actions to a minimum required value.
Sensitivity—a capability of providing an action on the operating conditions of a system whenever without such an action the operating conditions may go outside the permissible area without return to it.	*Selectivity*—a capability of providing an action on the operating conditions of a system only when without such an action the operating conditions may go outside the feasible area without return to it.
Reliability—a capability of providing sensitivity, accuracy and efficiency of emergency control actions under all emergency conditions considered in the design.	*High-quality control*—a capability of providing selectivity, minimum intensity and optimality of emergency control actions under all emergency conditions considered in the design.

With the first group of concepts (the effectiveness—optimality) considered, you see that the main difference between them is in the nature of the system return path, when the system goes outside the permissible area. In the first case, the constraints imposed on this path are not too stringent and the control equipment may be fairly simple, but in the other case the results may be better.

The second group of concepts (accuracy—minimum intensity) is associated with the fact that an entire domain of control $\mathbf{U}_d$, but not a single control u, corresponds to the relationship (8.5). This domain has been analyzed many times with regard to diverse power systems. It has been established that in certain cases it has a closed nature and the possibilities of utilizing enhanced actions are limited. e.g. there is a certain maximum of action intensity u_{max}, after which area S_2 goes outside S_{2d} boundaries. Naturally, such a control action must be fully rejected.

There is, however, another tendency to limit the actions intensity by a minimum value required to perform the emergency control functions and, thus, protect the system against excessive forces and strains and the consumer against detriment caused most often by some excessive decrease in the frequency. This tendency is quite justifiable, though, the practice has shown that such a detriment is perceived, but little, by the consumer, and to make the equipment too intricate to this reason is impracticable.

The relationship between the desirable and compulsory capabilities in the next group of concepts (sensitivity—selectivity) is somewhat different. The ability of the emergency control to find possible trajectory for the change of operating conditions of the power system outside the area is absolutely critical: without this ability the emergency control schemes will be unable to perform its functions. On the other hand, superfluous, unnecessary operation of individual devices may render the emergency control scheme practically inoperative. Hence, such a capability as selectivity is mentioned above as desirable. Nevertheless, it is often considered to be one of the most important abilities of the emergency control, and, if there is a risk of frequent, non-discriminating operation of the control schemes, then we have to agree to make the equipment a bit more complicated in order to prevent such phenomena.

The terms "sensitivity" and "selectivity" have come into the emergency control field from the protective relaying technology and are given herein a wider interpretation. In the protective relaying these concepts are mainly associated with the point of installing a protective device and type of fault, whereas in the field of emergency control they are also associated with the intensity of disturbance. More than that, in the protective relaying a quantitative difference between the normal load condition and short-circuit condition is usually fairly great, whereas in the emergency control technology

conditions threatening the system with forcing out of the permissible area are often close to conditions not involving such a risk. To satisfy these two contradicting requirements (sensitivity and selectivity) is much more difficult under the emergency control conditions than under the protective relaying conditions.

The generalizing concepts of "reliability" and "high-quality control" include all the above-discussed concepts. Therefore, we have only to say that the above material covers only the most general problems associated with the operating conditions requirements for the emergency control schemes which in fact are exceedingly detailed and contain hints both on the methods of controlling the performance of the system under emergency conditions and on the criteria of detecting disturbances in power system.

8.6. Effect of Emergency Control on Power System Operation under Emergency Conditions

Let considerations be given to the methods of controlling electromechanical transients in a power system and equipment used for the purpose that performs the emergency control actuator functions be characterized.

By principles of operation all emergency control actuators may be divided into three groups. The first group comprises the switchgear equipment (circuit breakers, contractors for electrical braking, etc.). The second group includes devices used to produce an action on the governors of prime movers. The third group is comprised by the devices controlling the excitation system.

As to their action, the actuators may fall into two classes: one to change the balance of active and reactive powers in the power system and the other to change the system configuration (sectioning, etc.). And what may be of interest, changes in configuration may often involve, as shown above, changes in the balance of power.

Therefore, the system transients are under a complex effect comprising a number of components which are often difficult to distinguish from one another.

For a complete list of actuating devices of emergency control and their actions see the block diagram of the emergency control scheme (Fig. 8.4). In view of this, considerations will be given herein only to those methods which are utilized in the emergency control early called *special* and are worthy of specific discussion. These methods include tripping of some generators, electrical braking, control of prime movers and excitation system of synchronous machines, and also certain new techniques still under development.

Generation rejection. In order to consider this technique successfully utilized by electric utilities in many countries for a number of years, use the two-machine model of a power system with the sending

end formed by a powerful hydroelectric station comprising enough generators.

For the sake of simplification let the station bus voltage be constant (at the beginning of the transmission line) due to the operation of the voltage regulators. In that, during the generation rejection operation, the excitation must be under the special control.

Proceeding from the assumed constant line voltage, an analysis of the system under generation rejection conditions may be performed directly through the use of the two-machine system swing equation, believing that the generation rejection (GR) leads to a decrease in P_m and some change in the deceleration in the time constant τ_j. However, in a first approximation, a change in the time constant may be neglected.

Analyzing the swing equation, we see that GR as a method of controlling electromechanical transients in a power system, possesses two important properties:

(1) It acts concurrently on the steady-state stability conditions during the after-emergency operation and on the transients dynamics.

(2) The effectiveness of actions on the process is dependent on the relationship of powers in the sending and receiving parts of the system, in particular on their constants τ_{j1} and τ_{j2}, provided referred to one and the same base value.

This property of GR is evident. A change in the balance of the shaft power of the generator units accomplished during a transition continues its action, in this event, even after the completion of transition. Note, that in this case, the acceleration area may be shortened in principle, the generation rejection (GR), however, occurs practically concurrently with clearing of a short circuit and even after it. Therefore, the acceleration area remains practically unchanged.

The possibility of simultaneous solution of statics and dynamics problems made the GR a multi-purpose means easy to use in practice. However, at least three disadvantages of this method may be noted which sometimes make us treat this method with care. These are:

(1) Long time taken by reclosing the generators switched off during the generation rejection.

(2) Impossibility of applying the action in small steps.

If there are, for instance, 20 generator units of small power in a power plant, then a GR step is 1/20 of the station rating value. If a power station comprises 4 or 5 large generator units, a GR step is 1/4 or 1/5 of the rating, which is too coarse and may lead to unjustified heavy demand disconnections.

(3) A comparatively low efficiency in the cases when powers of the receiving and sending parts are commensurable.

As it has been mentioned, a change in the relative motion of the system accounts only for part of the change in the power ΔP_m during GR, rather than for the entire change, and accordingly the trans-

mission line must be unloaded to a higher level. In order to prove this, determine how the power balance changes after GR in the equation (8.1) describing the relative motion in the power system. According to the equation (8.3) the value of ΔP_m is to be inserted into an equation with a coefficient $k = \tau_{j2}/(\tau_{j1} + \tau_{j2})$. If $\tau_{j1} \ll \tau_{j2}$, this coefficient approximates unity and almost the entire change of ΔP_m is affecting the relative motion. When, for instance, $\tau_{j2} \approx \tau_{j1}$, only half the ΔP_m affects this motion. The value of the deceleration area will decrease respectively.

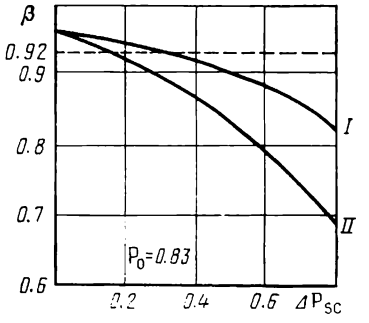


Fig. 8.6

Steady-state relations that are to be set after emergency conditions should meet the requirements for creating an 8-10% margin of the steady-state stability and, hence, a certain deceleration area always exists. The value of this plateau is calculated by the corrected value of ΔP_m.

If $\tau_{j1} \ll \tau_{j2}$ this area is so large that no additional generation rejection to meet the transient stability conditions is needed in most cases, when the main protection gear of the line operates within the time $\Delta t_{sc} = 0.12$ s, this being true for most often faults. If τ_{j2} and τ_{j1} are commensurable, a decrease in the power fraction affecting the relative motion leads to the necessity of generation rejection at a higher level, than it should be required to meet only the steady-state relationships.

What has been said is proved by curves shown in Fig. 8.6 illustrating the relative levels of load shedding

$$\beta = \frac{P_0 - \Delta P_m}{P_{12}^{II}}$$

where P_0 is the pre-fault load of transmission line for two cases: a system with $\tau_j = 12$ s operating into infinite busbars (curve *I*) and a utility comprising two parts equal in power each of which possesses the above-mentioned time constant (curve *II*). In the former case, even with a very large instantaneous decreasing of generators load as a result of a short-circuit ΔP_{sc}, the remaining load lies near the normal limit. In the latter case, it is badly dependent upon ΔP_{sc} and is found to be far lower.

Therefore, with systems of commensurable power, the P_m of the sending end of the line is to be more reduced and, hence, the result is a greater decrease in the power transmitted to the receiving system as compared to the pre-fault power. However, such a decrease is

undesirable in receiving systems of low power, inasmuch as receiving systems of great power suffer, but little from GR (a frequency fall level in this event is in terms of decimal fractions of Hz).

In view of this, opposing conditions arise which require additional measures for the system of commensurable power to sustain the transient stability.

Let now considerations be given to the control actions on the excitation systems during generation rejection. It is evident, that the higher the bus voltage at this time, the more efficient is generation rejection. In this event, however, no requirements, say, for damping oscillations are needed. At the same time, it is important to prevent the voltage regulators from reducing the excitations, whatever may be the conditions. Hence, when hydropower plants for systems of commensurable powers employ devices of forced control (voltage regulators with power system stabilizer), a specific pulse must be sent to compensate for a frequency fall during generation rejection.

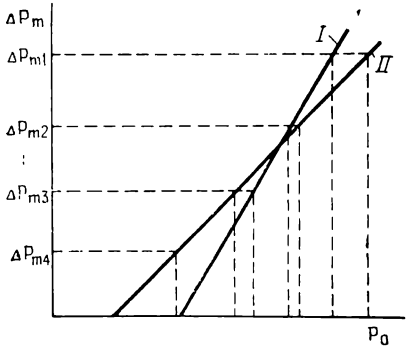


Fig. 8.7

Now let us consider the specific features of the generation rejection control. The requirement for a standard stability margin under the post-emergency conditions makes it possible to do no more during the GR control in a network of a powerful receiving system than to resort mainly to the steady-state relations, i.e. to choose the number of generators to be disconnected only to provide an 8% margin of steady-state stability under the post-emergency conditions. If that is the case, an elementary relationship between the power of the generation rejected and the initial demand on the transmission line:

$$\Delta P_m = P_0 - 0.92P_{12}^{II} \tag{8.6}$$

where P_0 is the initial (pre-fault) load on the transmission line; P_{12}^{II} is the steady-state limit of the power transmitted for this transmission line under the post-emergency conditions.

For a graph of this relationship see Fig. 8.7 which illustrates it with due regard to the diagram in Fig. 8.1, for the two operating conditions of this diagram—normal *I* and outage *II*. In that, the latter mode of operation is characterized by disconnecting one of the parallel circuits in the first section of the transmission line with a circuit earlier tripped in the other section of it.

Relations like these after their piecewise constant approximation in steps (in compliance with the power of generators rejection) are inserted in the control device to provide the necessary commands during a fault. These commands must be interpreted in accordance with the actual load on one or another machine before the emergency conditions, for which purpose the load must be monitored and the number of generators to be switched off must increase, if necessary. Besides the simple case considered, however, there are more complicated situations for which intricate calculations should be carried out to determine the relationship between ΔP_m and P_0. In that, the value of P_0 is related to several lines and we have to sum up the powers or resort to another functional transformation. There are instances (true, these are not frequent and concern mainly system with two parts of commensurable power) when the values of $\Delta P_{s.c}$ and other like values should be taken into account.

Electrical (electrodynamic) braking. This is a natural method of killing excessive kinetic energy of the generator unit rotors by connecting special load resistors (LR) to them. The study of this method used to preserve the stability of power systems under emergency conditions is of methodical importance, as it is in this method, that many of the essential properties of similar methods manifest themselves most clearly.

Considerations have been given in braking devices under design to diverse types of LR: metallic (air-cooled) resistors, metallic (oil-cooled) resistors, and also Soviet made so-called "betel" resistors, i.e. resistors of specific electrically conducting concrete. These devices are distinguished not only by the fabrication methods, but also by their nominal dissipation power that is determined as a power consumed by the resistor at the nominal voltage across its terminals.

Studies were made of resistors from 400 to 2 000 MW. Though the LR are designed to be turned on usually for several seconds, resulting power dissipations are large. To achieve this, use is made of large dissipation surfaces. More than that, the resistors are sometimes provided with the necessary high-tension insulation and are rather massive. Anyway, they are huge and expensive devices.

Specific contactors of load resistors are also rather intricate and massive. They should not interrupt inductive currents which, naturally, makes their construction easier. In this event, however, very short switching times should be provided (of the order of 0.04 to 0.06 s). Besides, the contactors must be reliable, since the stability of the entire power plant is dependent on performance of such a contactor.

Initially all devices for electrical braking were designed as a single installation connected at the H.V. side of the power plant (usually at 500 kV). Later, other designs appeared, providing either several LRs on the high-voltage side, or a series of LRs on the generators

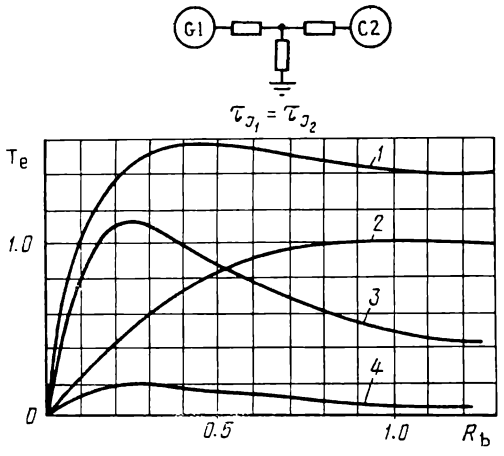


Fig. 8.8

terminals (one per a generator). If that is the case, the problems of braking power redundancy and varying it become easier. However, other problems arise. Examples are problems concerning LR arrangement and connection to the circuit of the switchgear.

Comparing LRs operating at the high and generators voltages shows that under the same rated power the braking efficiency is the higher, the shorter the electrical distance between the LR and the generator terminals (the lower the impedance between them). Indeed, with LRs connected to the H.V. buses (after the transformer), the voltage across them in the processes of braking abruptly drops and the resultant decelerating power decreases. More than that, with the value of τ_{j2} commensurable with τ_{j1}, the intensity of braking and its efficiency are affected by reducing the power fraction affecting the relative motion. The farther (electrically) is the LR from the generator, the stronger the effect of this phenomenon.

Hence, LR installed under the generators voltage is always more efficient, than that under the high tension.

Each system has its own maximum decelerating power that can be developed across LRs, its value being under the effect of all abovementioned considerations. This can be demonstrated by calculations made with regard to a pool comprising two parts of commensurable power interconnected by a 500 kV line 600 km long.

The calculations have been made, proceeding on the assumption that the e.m.f. beyond transient reactances of the generators remains constant, the effect of the line load being neglected. The resistor was considered to be connected to the H.V. buses of the station (at the beginning of the transmission line). The results are shown in Fig. 8.8 illustrating the electromagnetic power in fractions

of a unit during electrical braking *versus* the steady-state limit at $R_b = \infty$ (*1*—total power, *2*—mutual power, *3* and *4*—powers of the sending and receiving parts). Referring to the diagram, the effect is seen of individual components on the overall decelerating power $P_{e.b.}$ (more precisely, on the maximum of the power angle characteristic of the transmission line under consideration), when the value of the braking resistance R_b varies. A clearly seen maximum would be obviously higher, if the resistor were connected to the generator voltage.

As the next step, let us consider the braking process. As to the operating principle, there are two types of braking control schemes. These are single-action braking intended only for killing excessive kinetic energy during the transient, and multi-action braking capable of maintaining the power balance under post-emergency conditions during the time taken to reduce the mechanical power available at the station through the control of the turbines (by turbines are meant hydraulic turbines in which power reduction after a load surge takes several seconds).

Single-action braking. With transmission line furnished with auto-reclosure devices this type of braking is sometimes treated as double-action, and planned to be used directly at the instant of short-circuit (i.e. to reduce the acceleration area). Recently, however, when faults are isolated by the main protection equipment within 0.12-0.15 s switching a load resistor into the circuit plus the action of the control apparatus take almost the same time as fault clearing (sometimes even more time).

Under such conditions the electrodynamic braking is able to influence only the deceleration area, the low bound of which shifts in this case down for a certain value ΔP_b.

An increase in the deceleration area might be used as a quantitative measure to evaluate the relations arising therefrom.

An analysis of this process on the phase plane, however, represents a method still clearer. Figure 8.9 shows a family of boundary phase trajectories of a transmission line ($P_{01} > P_{02} > P_{03}$). A bold line illustrates the boundary trajectory of the post-emergency conditions under analysis. The line δ_0-$\delta_{c.s.}$ in the diagram stands for the acceleration trajectory of the generator unit under short-circuit conditions. It is supposed that the fault causes no power surge, i.e. $P_m < P_{12}^{II}$.

The deceleration area in this case, however, is not enough to compensate for the acceleration one. As a result, the path of deceleration without connecting an LR (dash-and-dot line in Fig. 8.9) does not cross the zero line and turns towards the area of large slips, forming specific point of a "saddle" type. Thus, the kinetic energy stored by the generator unit rotors under the emergency conditions is too great to be killed naturally.

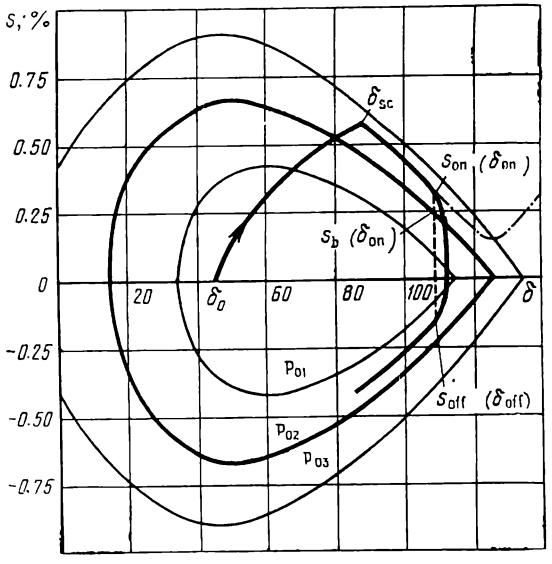


Fig. 8.9

Switching the LR in at the point S_{in} shown in the diagram (Fig. 8.9) abruptly changes the further path of the system and with a sufficient capacity of the LR the path crosses the zero line, i.e. the transient stability is provided.

When analyzing the process of the braking on the phase plane pay regard to the fact of importance, that a large capacity of an LR makes the phase trajectory turn abruptly down after the LR switching. This may be approximately replaced with a straight dash line shown in Fig. 8.9. This means that the real motion of the system over this path section is replaced with a uniformly decelerated motion the equation of which in the time area has the form

$$s = (\Delta P_b/\tau_j)\, t \tag{8.7}$$

Referring to the equation (8.7), determine the parameters of the braking pulse. These are the power ΔP_b and duration T_b. Proceeding from the properties of the boundary phase trajectories, you can easily see that, if the switching is made at the angle δ_{in} and the amplitude of the boundary phase trajectory in this event is S_{bound} (δ_{in}), then to provide the transient stability, it is necessary and enough to have

$$\Delta P_b T_b \,|_{\min} \geqslant \tau_j \,[s_{in}\,(\delta_{in}) - s_{bound}\,(\delta_{in})] \tag{8.8}$$

This method may also be used to determine the value of a critical pulse of braking at which the transient stability remains still pre-

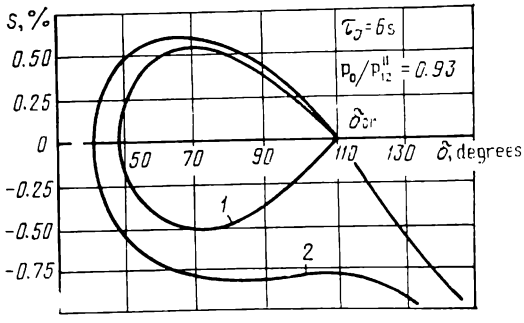


Fig. 8.10

served. Referring to Fig. 8.9, this pulse may be found as follows:

$$\Delta P_b T_b \mid_{\max} \leqslant \tau_j \left[s_{in}\left(\delta_{in}\right) + s_{bound}\left(\delta_{in}\right)\right] \tag{8.9}$$

Therefore, even at similar faults the value of braking pulses $\Delta P_b T_b$ (usually only T_b varies) must not be absolutely precise and may lie within a certain range from $\Delta P_b T_b \mid_{\min}$ to $\Delta P_b T_b \mid_{\max}$. In that, referring to Fig. 8.9, you can see that the higher the load of the transmission line (the greater the value of P_0), the closer are these limits.

The above method of replacing phase path arcs with straight lines may find its applications not only in the analysis of the electrical braking, but also in a number of other analyses of transients under the emergency control. It should be kept in mind, that the phase paths (Fig. 8.9) correspond to the so-called conservative idealization of a system that can be seen from the swing equation (8.1).

In reality, dissipative forces are always present in power systems and a term with the first derivative of the angle δ (often $k_s\, d\delta/dt$, where k_s is inherent regulation factor) must be inserted into the equation of motion. This circumstance alters the form of the boundary phase path as shown in Fig. 8.10 in which the trajectory of conservative system *1* is compared under the same operating conditions with the path of dissipative system *2*. It follows from this comparison that in reality the area of permissible negative slips is somewhat larger than the case is with the conservative idealization. Besides, the used pulse of braking $\Delta P_b T_b$ may be somewhat higher. In that, the higher k_s, the larger the amount of this pulse growth.

The above example of emergency conditions without power surges can be readily applied to a fault with a power surge, i.e. where $P_0 > P_{12}^{II}$. In this event, however, the electrical braking (EB) should be accompanied by any other protective action providing the steady-state stability conditions after switching off the braking load resistors. Such an action may be, say generation rejection (GR), which is often considered in conjunction with braking under transient conditions.

Multi-action braking. It has been stated above that the single-action braking is intended for the use at faults with no power surges, otherwise it should be used in combination with GR. A unique method has been elaborated in this country which allows transmission line unloading without GR, solely on account of the turbine control and braking.

The problem in this event was formulated as follows: let a fault occur in conditions when $P_0 > P_{12}^{II}$. It is required to provide a stable transition with changing the turbine power P_m by operating the turbine control (a hydraulic turbine is meant). A power change process in this event takes several seconds, while imbalance between electrical power P_e and mechanical power P_m will cause the stability loss within fractions of a second.

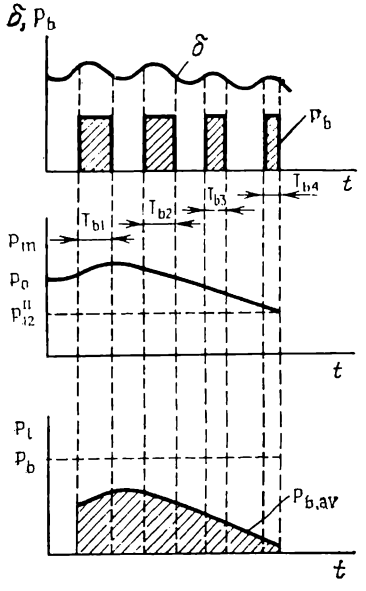


Fig. 8.11

Therefore, there must be means of sustaining this balance over the mentioned period. Moreeover, the means should be such that it would be capable of sustaining the balance despite the fact that the imbalance value varies continuously with the turbine control process (since P_m varies).

A continuously variable load resistor would be an ideal facility of facing this problem. However to build such a resistor for the required capacity is impossible or unpracticable and use should be made as before of LR having constant power capacity. A solution was to utilize a series of braking pulses different in length, so that the mean value of their power corresponds to the current value of imbalance $P_e - P_m(t)$ with braking neglected. This principle is illustrated in Fig. 8.11 which shows changes in the mechanical power of the generator units during the turbine control and also changes in the transmission line load P_l and pulses P_b.

The process depicted in this diagram is characterized by oscillations of the transmission angle δ which grows when the resistor is disconnected and drops when it is connected.

These oscillations, however, are small and we may think of a certain mean load power of the transmission line P_{lm}. Then, the multi-action braking may be thought of as a method based on the expression:

$$P_m(t) - P_{lm} - P_{bm} = 0 \qquad (8.10)$$

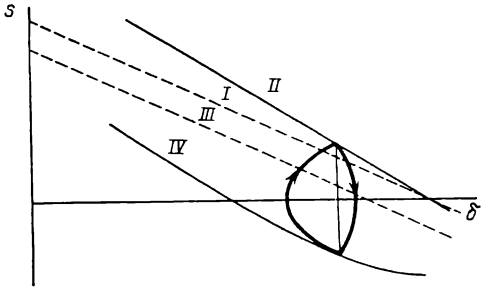


Fig. 8.12

where P_{bm} is an averaged power of braking pulses that is a shaded zone in Fig. 8.11.

By its nature the above method approximates other pulse control methods utilized in the automation technology. It is clearly illustrated by the diagram in Fig. 8.12 in which a braking process is shown on a phase plane. The diagram shows a line of braking relay operation—*I*, a line of switching in an LR—*II*, a line of relay reset—*III*, and a line of switching out the LR—*IV*, one cycle of braking being shown by a bold line. This cycle is comprised by the acceleration trajectory with the LR disconnected (the left-hand part of the cycle) and the path of braking with the LR connected (the right-hand part of the cycle). Each such cycle corresponds to a certain value of the turbine mechanical power $P_m(t)$ and is characterized by its parameters such as pulse duration T_b and interval duration T_i. It is evident, that to maintain the zero imbalance condition the pulse parameters are also changed with changes in the turbine power. Because of the control method used here (in a function of the angle and slip), the switching over points at joints between the paths of acceleration and deceleration (braking) will move along their corresponding lines in the diagram (Fig. 8.12), i.e. the lines of switching in and out. As a result, there will be self-sustained oscillations with a variable period and on-off time ratio (T_b/T_i = var), which must cease after the mechanical power of the turbine being changed reaches the required value determined by the steady-state stability conditions after the fault has been cleared.

Such an organization of the process, i.e. provision of sustained self-oscillations at absence of steady-state stability conditions and stopping of these self-oscillations after the conditions were obtained makes up the main objective of the control of this process and will be discussed later.

It should be only noted herein, that the single-action and multi-action braking (deceleration) techniques differ much from each other as to the requirements for load resistor (LR).

Actually, on the single-action braking the load resistors have only to absorb excessive kinetic energy ΔV stored by the generator unit rotor during the fault, while on the multi-action braking, the LRs must in addition absorb all energy released over the period T_{im} of imbalance between $P_m(t)$ and P_{lm}:

$$W = \int_0^{T_{im}} [P_m(t) - P_{lm}]\, dt \tag{8.11}$$

This value usually is at least 5-10 times the value of ΔV, for which reason the LRs involved should be designed to carry far greater heat loads and, thus, they are more massive as compared to those used in the single-action braking. More than that, the requirements for LR contactors used in the multi-action braking are more complicated, as the contactors must be designed to perform 5-10 braking cycle reclosures.

These circumstances still hinder with the introduction of the multi-action braking technique into practice. However, this method forms a reserve of the emergency control as a facility of interest for most intricate cases of emergency control.

Let now considerations be given to the *control of braking (deceleration) process.* Various principles were proposed to control the single-action braking process that make it possible to select the duration of the braking pulse T_b as dictated by the gravity of the emergency conditions. In particular a suggestion was made to use an analogue of acceleration of generators, i.e. the value of an active power shedding in the moment of a short-circuit ΔP_{sc} or a combination of this value and the value of slip. In the case of multi-action braking use should be made of the value of the transmission angle δ and slip s. These values are combined in a special relay, the current in which is

$$i_r = i_{op}\,(\delta/\delta_{op} + s/s_{op}) \tag{8.12}$$

where i_{op} is the operation current of the relay; δ_{op} and s_{op} are segments cut off by the relay characteristic on the axes δ and s.

This characteristic represents a straight line known as *operate line.* Multiplying ordinates of this line by the drop-off-to-pick-up ratio $k_{d-p} < 1$ will give us the reset line (dash lines in Fig. 8.12).

Crossing the switching-in line by the phase path causes a pulse to switch in the LRs and when it crosses the reset line (*III*), a pulse is sent to switch out the LRs. However, the switching in and out actions proper are delayed with regard to the crossing points for the functioning time of the contactor, which in this event must be taken into account. Note that with this time constant, the distance between the relay operation lines and contactor operation lines on the phase plane is different as it is dependent on the system speed at a given point of this plane. This accounts for the nature of the switching-in

and switching-out lines shown in Fig. 8.12. The position of these lines should provide the suppression of self-oscillations on the ascending branch of the transmission line angle characteristic near its maximum. It is this condition that is a basis for selecting the settings of the relay in question.

Fast turbine control (FTC). This method of controlling the electromechanical transients in power systems consists in direct changes of the mechanical power of the generator units through effects on the control of the steam turbines.

That this method can be used and used efficiently for the purpose has been clear still at the beginning of the work on the power system stability problems. However, utilizing it in practice has required many researches and developments complicated by the "interface" nature of the problem which concerns the electrical, thermal and mechanical phenomena.

Research work on the use of fast turbine control to improve the system stability was started at the end of the 1920s and the early 1930s,first in the USA, and then in the USSR. At that time protective relaying of power systems and circuit-breakers used on power transmission lines featured a slow operation speed and the fault clearing time even for the main protective gear was as large as 0.5-0.7 s.

The control valves of turbines still then were fairly rapid-action, otherwise they could not prevent the generator unit from a considerable rise in its speed, when in a sudden disconnection from the network, the unit looses all its electrical load. In view of this, the control systems were required to be capable of fully closing the control valves under these conditions within about 0.25-0.3 s.

Therefore, it might be thought that the above mentioned valves would be closed till fault clearing, provided there was a specific device to produce the required signal and send it into the control system of the turbine.

This underlays the FTC principles developed in those years. However, as early as during the investigations it had been revealed that even complete closing of the valves of a turbine did not lead to killing its mechanical power fully. Because of an intermediate steam-filled space found between the control valves and the control stage of the turbine, the power drops gradually, the drop materially lagging the valve closure.

What is more, the conditions under which FTC is used in power system have changed very much since then. Naturally, the introduction of more advanced (say a carrier current type) protection gears and allover use of air-blust circuit breakers have made it possible to cut down the fault clearing time to 0.12-0.2 s (true of today).

Therefore, as the case was with the electric braking, the nature of the problem gradually varied. The FTC became considered as a facility of increasing the possible deceleration area (in place of

decreasing the acceleration one). It is this, that makes up the heart of the method described in this paragraph.

How the operating conditions of power systems have changed since the beginning of research work on FTC is also shown by arising of one more problem—a problem of protection against power surges which call for a quick change over of the generator units to another level of load corresponding to the new limit of steady-state stability. As is known, in generation rejection (GR) problems of sustaining stability under transient conditions and unloading of the transmission line under steady-state conditions are solved as a single whole. In the case under study the emergency control actuator is such that these problems may be tackled separately. In that, the problem of line unloading is treated as a specific problem known as a problem of emergency power limitation (EPL).

The conventional methods of mating the hydraulic systems of turbine governor with electrical devices of automatic load-frequency control turn out herein to be of no use. Really, the motor of the speed changer (SC) used to control the turbine load under normal conditions is fairly slow. Besides, as to its principle of operation it is of an integration type, whereas the electrical input to the turbine governor system in the case in question must be another. It must be quick-acting and, if possible, provide proportional action. This input is formed now by an electrohydraulic converter (EHC) made for the purpose which allows electrical pulses acting in parallel with the mechanical signals from the centrifugal speed sensor and the signal from the SC to be entered in the control system.

The design of an electrohydraulic converter by itself represents a complex problem which has been successfully solved. All Soviet-made steam turbines, rated for 300 MW and more (200 MW generator units are furnished with converters on special order) are equipped with electrohydraulic converters that make it possible to input pulses of high intensity into the control system at a delay of 0.03-0.05 s or less and organize a process of forced closing of steam admission to the turbine, in order to improve the power system stability. The essence of this process is a short-time deep drop of the generator shaft mechanical power providing for the generator unit deceleration by its electrical load. The actual flow of such a process depends, however, on the properties of the turbine as a controlled unit.

Let considerations be now given to a *turbine as an emergency-controlled system.* The introduction of emergency control has lead to the use of a new mode of operation of turbine control systems which exceedingly differs in its nature from their operating conditions under conventional load frequency control. Under normal operating conditions compensated for are small deviations of the parameter being regulated and the control systems of turbines generally operate in linear area as proportional amplifiers of the pulses from the

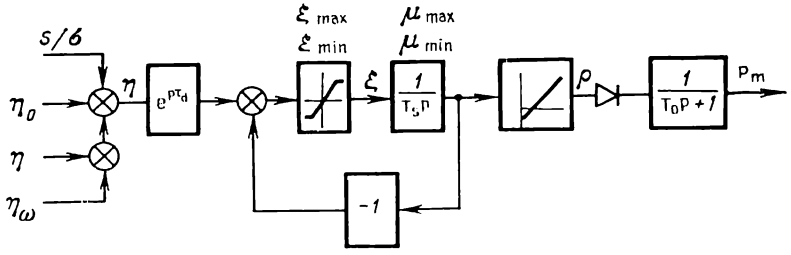


Fig. 8.13

centrifugal governor and speed changer. Under emergency conditions the performance takes place at heavy control pulses forcing the system elements outside the linear area as far as they will go.

In this case, use is made of the method usually encountered in the pulse automatic control in which control pulses are varied in duration, rather than in their amplitude. The said means an alteration of the turbine model with some departure from the conventional notions that are usually thought of in the planning of normal operating conditions. As a rule in load frequency control investigations use is made of a linearized model of a turbine without considering the nonlinearities (stops), but in this case we may not do so.

A complete model of a turbine simulating all basic characteristics of it is fairly complicated and very difficult to be used as an analytic tool. In view of this, another model was elaborated intended for the emergency control investigations. It well depicts the qualitative aspect of the process and even allows some quantitative assessment.

For the block diagram of this model see Fig. 8.13. The model input comprises pulses η_ω (from the speed governor), η_0 (from the SC), and η_e (from the EHC).

The model input is formed by a pure delay element accounting for the delay in the transfer of pulses from the mentioned devices to the other elements of the control system. The other components are:

a slide valve and a servomotor to control the turbine valves together with a negative feedback unit;

a member of coupling between the servomotors and the valves that illustrates the nature of this coupling;

an element (a valve) standing for the turbine valves proper;

an element standing for the entrained steam in the turbine.

This model, though unlike the conventional one (no leverage couplings that are replaced with hydraulic and even electrical ones and are most often absent in modern turbines) is enough close to the earlier model and includes the same essential elements. And yet, the given model has specific features of importance:

(1) The mass of the centrifugal sensor weight balls is not taken into account, and all the elements intended for the amplification of the pulses from intermediate amplifiers (till the slide valve of the main servomotor) are substituted for by one element of pure delay having delay time τ_d. With small oscillations such a substitution is not correct. With large pulses, however, all amplifiers have no individual effects in practice and the use of one element allows such an effect to occur without complicating the model.

(2) The stops (constraints) are taken into account as to all basic coordinates which is an inherent feature of a non-linear model. These constraints are indicated in the diagram by symbols found above the corresponding elements.

(3) The model does not account for the dynamics of steam reheaters.

Let the third specific feature be considered in more detail. Almost all generator units of power plants that utilize or are to utilize FTC represent units furnished with steam reheaters found between the H.P. section and L.P. and I.P. sections. Therefore, considering the process dynamics calls for the account of steam inertia in such reheaters which is fairly great. In analyzing small oscillations, when only turbine control valves are operating, this inertia must be considered. In the case of large oscillations, however, the control valves are assisted by the intercepter valves which separate the I.P. and L.P. sections from the superheater.

Thus, changes in the steam admission to the I.P. and L.P. sections occur almost concurrently and in parallel with the changes in the steam admission to the H.P. section. If that is the case, the series chain of high-, intermediate- and low-pressure sections becomes as if converted into two parallel chains which may be thought of as two individual turbines with no intermediate superheating controlled in parallel and simulated by one common overall model.

Such an approach to the problem is certainly not enough rigorous, but it is suitable for both qualitative and preliminary quantitative assessments of the processes and phenomena under the FTC conditions. If an exact quantitative assessment is required, use should be made of more precise models.

Let now the processes occurring in the turbine models, when emergency control pulses are applied to it, be analyzed with due regard to the above-made notes. In this analysis we shall proceed from the following scale relation in the model. With the servomotor movement coordinate a value $\mu = 1$ corresponds to the full nominal power capacity of the generator unit and $\mu = 0$, to the no-load operation.

The input pulses are measured in specific units. Such a unit is defined as follows. Assume the frequency of the system including a given generator unit to vary for a quantity $\Delta f = \sigma f_{nom}$ where σ is a static slope or generator unit speed regulating nonuniformity; f_{nom} is a nominal frequency.

If that is the case, the turbine will take the nominal load, if it has been unloaded to zero prior to such a frequency variation. The loading will be performed on the signal η_ω from the speed governor. It is the value of a signal at such a frequency variation that is specified as a measurement unit for all input signals.

In the turbine control publications and emergency control technology the signal of the mentioned value is measured with a unit known as a *variation* (v-n). The same units are also used to measure port opening of the slide valve of the servomotor. A fact of importance is the presence of limits in opening the slide valve ports, the limits being different in increasing and decreasing the steam admission to the turbine. In that it should be kept in mind, that the value of the time constant of the servomotor T_s is the time it takes to move from $\mu = 1$ to $\mu = 0$ and return back at $\xi = 1$. In reality, however, with the limitations taken into account, the speeds of servomotor motions determined by the full motion of the servomotor are as follows:

When moving from $\mu = 1$ to $\mu = 0$

$$T'_c = T_s/\xi_{max} \tag{8.13}$$

When moving from $\mu = 0$ to $\mu = 1$

$$T'_{op} = T_s/\xi_{min} \tag{8.14}$$

In most cases, it should be taken into account that the servomotor may move down beyond the point $\mu = 0$ for a certain negative magnitude μ_{min}. Besides, due to the turbine ability to carry overloads, the value of μ may sometimes reach $\mu_{max} > 1$. In view of this, use is often made of the so-called intrinsic time of a servomotor, i.e. the time it takes to move from stop to stop, in place of its time constant T_s. In the case of closing the servomotor intrinsic time may be determined as follows:

$$T_{c.\,int} = T_c\,[\mu_{max} - \mu_{min}] \tag{8.15}$$

It is this latter value that is used as an experimental value to determine T_s.

Assume now that a pulse having a duration $T_p < T_c$ and an amplitude $A \gg 1$ is applied to the input of the control system of a turbine operating at $\mu = \mu_0 = 1$. This will initiate a forced closing of the steam admission to the generator unit. This process is shown in Fig. 8.14 with reference to a turbine model used for various pulse durations. Injection of a large pulse of amplitude A will at once move the slide valve of the servomotor to its bottom dead centre—position ξ_{min}, and the servomotor will start its closing movement at the full speed $1/T'_c$. Its displacement will produce a negative feedback pulse applied to the slide valve $(-\mu)$. This

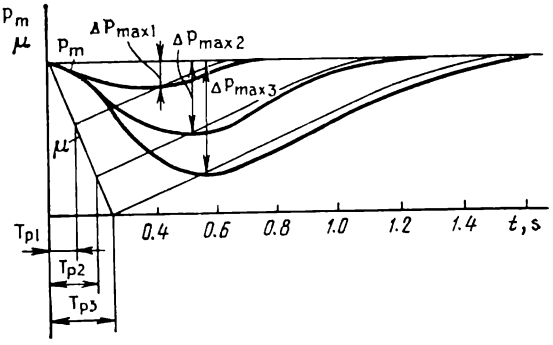


Fig. 8.14

pulse, however, will have no effect on the slide valve, unless there is a disturbance to the condition:

$$A - \mu \geqslant |\mu_{min}| \tag{8.16}$$

Properly selecting the value of A, this condition can be satisfied in motion from $\mu = 1$ to $\mu = 0$, i.e. the servomotor can operate at a constant maximum speed. This mode of operation is shown in Fig. 8.14. In that, the servomotor starts its motion μ at a bias of τ_d, rather than the instant the pulse is applied.

Biasing under effect of the pulse A, the servomotor will move in the pulse duration time T_p a distance

$$\Delta\mu = \xi_{min}\frac{1}{T_s}T_p \tag{8.17}$$

which will produce a negative feedback signal $-\Delta\mu$. After the pulse has been removed, this signal will cause the servomotor to reverse. In that (since $\xi_{min} < 1$) the reverse motion will first be at a constant speed and then the speed will start to drop and will aproach the initial point along an exponential curve.

As the next step, trace the change of the turbine mechanical power shown in an assumption that the union between μ and ρ over the section $\mu = 0$ to 1 is linear. The presence of an entrained steam included in this model in the form of an aperiodic element leads to that the change in the power materially lags the run of the servomotor. The time constant of the extrained steam T_0 is commensurable with the time T_p and constant T_s. As a result, changes in the value of P_m can be detected generally at the middle or end of the closing motion of the servomotor.

An effect of the servomotor motion reversing, after the pulse diminishes, on the mechanical power value is also delayed, and it is readily seen in this model, that the minimum of this value always

coincides with the point where the lines μ and P_m cross each other. Therefore, a linear in time change in the position of the servomotor causes a short-time deep drop of the mechanical power with reaching a certain minimum value P_{min}. A maximum power change in this process ΔP_{max} is its main characteristic and represents a linear function of T_p. It is this reduction of mechanical power that is utilized to increase or create, if necessary, a generator unit deceleration area during the transients.

The model in question allows us to simulate mechanical power reduction processes under different conditions, i.e. at various values of pulse duration T_p, servomotor time constant T_s, constraints ξ_{max} and ξ_{min}, and time constant of entrained steam T_0. In this case, of importance are the nature of the coupling between the servomotor and the control valves of the turbine, and also the presence of a stop by the coordinate μ, specifically a bottom stop μ_{min}. The latter circumstance leads to that with the pulse of enough duration the servomotor may remain for some time on the stop which disturbs the linear relationship between T_p and ΔP_{max}.

The quantitative relations characteristic of this process may be obtained from a set of differential equations (describing the model elements) which is solved by the curve-fitting method, e.g. by calculating changes of P_m by individual segments of open polygon μ. In doing so, the results obtained at the end of a previous segment are used as the starting conditions for the subsequent segment. This method allows us to obtain curves of P_m changes in time, and also ΔP_{max} against T_p which are known as *pulse characteristics of turbines.*

In practice use is made of experimental characteristics obtained during special tests performed on actual turbines. Moreover, the form of these characteristics may be judged from the said above. With the pulse duration T_p relatively small, when μ still not yet reaches μ_{min} the relationship between ΔP_{max} and T_p is practically linear, i.e.

$$\Delta P_{max} = kT_p \tag{8.18}$$

When μ reaches μ_{min} and for some time stays on the stop, a far less increment of ΔP_{max} corresponds to large changes in T_p, i.e. the characteristic obtains a section of saturation.

In order to make the process of power change under FTC conditions smoother, use is sometimes made of pulses having an amplitude reduced to 1.5-2 v-ns. If that is the case, the process mechanism becomes essentially different and all relations change as well.

Considering the processes of changing P_m under FTC conditions, an essential change in P_m takes place far later after the instant a short-circuit is cleared. Earlier this circumstance was considered to be an obstruction to the use of FTC. Investigations however

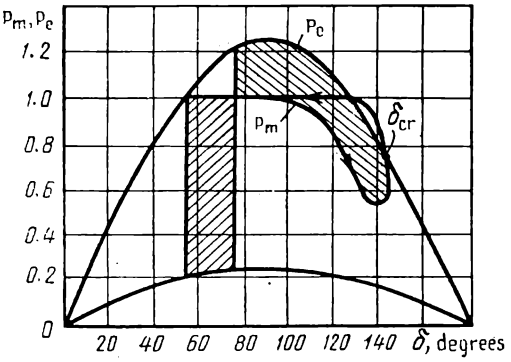


Fig. 8.15

have shown that an increase in the deceleration area obtained in this case is of great importance. Actually, any decrease of P_m in this event means not only a decrease in the generator unit acceleration rate, but an increase in the critical angle $\delta = \arcsin (P_m/P_{12}^{II})$ which sets a limit to the transient stability of the generator unit. Thus, a two-fold effect takes place that materially adds to the possibility of holding the machine in synchronism.

To clearly ascertain this, let considerations be given to the angle diagram (Fig. 8.15) in a case of a line short-circuit. This diagram also shows a pattern of changes in P_m in the form of a function of the angle δ. Referring to the diagram, in the initial stage of δ growth the value of P_m varies but little and the acceleration area remains the same as without FTC. On the other hand, in the final stage in which the rate of δ changes should rise, P_m begins to essentially drop leading to a double effect.

Creating a required deceleration area and killing excessive kinetic energy of generator unit rotors, P_m may be increased to values tolerable under post-emergency conditions. However, to a series of reasons considered later on, the rate of such an increase is artificially slowered, when proceeding to the solution of another (not related to FTC) problem, i.e. reducing of the power level that will support the control of the turbine under the post-emergency conditions.

Digressing for the present from the actual method of solving the problem, we only note herein that the turbine control is acted upon in this problem far less intensively, than in the case discussed earlier, for which reason an action upon the limiting of power may be treated as a special signal imposed on the pulse action to preserve the transmission steady-state stability. This signal is termed an *emergency power limiting signal.* It can be applied either through an EHC, or SC.

A complex process of acting upon the change of the mechanical power of generator units arises thereby which provides for both the transient stability (killing excessive kinetic power) and the steady-state stability (transmission load limiting under post-emergency conditions). As to the improvement of the power system stability efficiency of this method is dependent on a large number of factors. Essential effects herein are produced by the thermal and mechanical parameters of the system. The transient stability is influenced by values of T_0 and T_s (more exact, $T_{c.int}$). The steady-state capabilities are dependent upon the critical permissible level of unloading boiler units.

As is shown by investigations and calculations, with $T_{c.int} \approx$ ≈ 0.2 s and $T_0 \approx 0.25$ s typical of advanced turbines, the transient stability of transmission system can be increased about 10-15%. In most cases the permissible level of post-emergency unloading, which is about 30-50% for generator units carrying full load, turns out to be enough to tackle problems arising in power systems.

Let an analysis be now made of the specific features of the control under FTC technique. With this method of acting upon the emergency operating conditions the control problems are of utmost importance. They undergo a long-time and thorough study. Initially, most simple methods were proposed based on detecting load drops during short-circuits, which are equal to $P_m - P_e$ and serve as a measure of unit acceleration. Then, use of special governors was put forward with a view to sustaining the turbine power under a short-circuit conditions at the level of the generator load. Their introduction into practice, however, coincided in time with an abrupt acceleration in the performance of the protection gear and switchgear. As a result, those governors failed to perform their functions in a proper manner which was also hindered by a considerable value of the time constant T_0 of entrained steam (up to 0.25 s for modern turbines). Whereas, the time of clearing a short-circuit is 0.12-0.2 s. So, the use of governors of this kind became impossible.

Today the widely used control of turbine is by high-amplitude pulses whose flow in the turbine control system has been described above. In this case, however, a number of problems arise which call for special discussion.

1. **Pulse shape.** Investigations have shown that with a pure square pulse, the rate of load restoration of modern turbines is such, that deep swings may result causing loss of stability. This may be avoided either by specially organized damping of such swings effected through sending several repeated pulses of reduced duration, or merely by decelerating the turbine power restoration through the use of special-shape pulse having a slowly (exponentially) drooping trailing edge. Today use is mainly made of the latter method with pulse shape

shown in Fig. 8.16 and provides for a material delay in deenergizing the EHC. This decelerates the opening of the control valves of the machine and, thus, the restoration of its power.

2. **Methods of control pulse generation and criteria.** In many respects these are dependent on the configuration of the power system and operating conditions in it. A most simple case is when a power plant operates through a transmission line into a large power system, the local load on the plant buses being null or negligible. In this event, nothing more than the fact of a fault should be taken into account in selecting the pulse duration. The pulse itself may be intended for a heaviest fault, inasmuch as it will be of no danger both to the turbine and to the system.

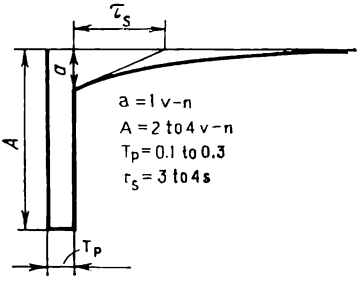


Fig. 8.16

Quite another thing, if there is a sizeable local load on the buses of the power plant. This situation is illustrated by curves shown in Fig. 8.17 and plotted under the following conditions: a short-circuit of fixed duration with various generators load drop ΔP_{sc} was simulated in the depicted system. In that, by gradually increasing the pulse duration T_p, the stability loss could first be simulated with a transition into a positive slip (underbraking), then stable transitions, and then again the stability loss with a transition into negative slip (overbraking). The phase contours associated with points *a*, *b* and *c* are shown in the diagram.

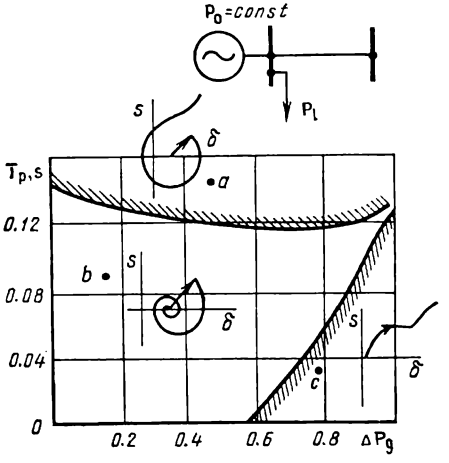


Fig. 8.17

Therefore, even in this relatively simple case, the stability domain resulting from the use of this method turns out to be of closed type, and the control must be conducted with taking into account the value of ΔP_{sc}. More complicated instances may be encountered in actual power systems, in which case the emergency control and emergency power limiting should be accomplished on a basis of large amount of information collected and processed by the so called com-

plex devices of automatic control (see 8.7). The value of T_p in this event is selected against a model. By way of a first approximation the following rule may be recommended: during the unloading process P_m should not drop below P_l.

Action on Excitation System. The action on the excitation system under emergency conditions is one of the most old, simple and efficient methods to control electromechanical transients in power systems. As the case is with the effect on the prime mover, this action at faults must be forced. It is this action that will be considered later, regardless of the device producing it.

Early in the years of settling down the techniques of transmitting power over long distances, suggestions to boost excitation under short-circuit conditions were strongly objected to, since it seemed that the result would be a material increase in the current flow. Later, however, with modification of transient nature, in particular, with the reduction of fault duration, this point of view essentially changed, and it became clear that collapses of voltage could not be tackled without forcing the excitation, as could not be performed a number of other functions, the main of which was provision of high levels of voltage under post-emergency conditions and damping oscillations.

Today, when the problem of maintaining stability at faults causing power surges is thought of as the main one, and when the power systems utilize such powerful means as GR and FTC, the above-mentioned functions may be handled as auxiliary ones. Nevertheless, numerous investigations and computations have shown that low quality of auxiliary functions may affect badly the results of basic measures and actions.

Therefore, the requirements for the action on the process on the part of the excitation system remain fairly high, and it is urgently needed to understand well what factors influence the execution of these requirements and the efficiency of a given effect as a whole.

It is known that the basic requirement to the excitation system at faults in power systems comes to speeding up the voltage restoration after a fault. This makes it possible to obtain maximum possible values of P_{12}^{II} immediately after a short-circuit and accordingly a maximum area of possible deceleration. To this objective, however, the generator electromagnetic inertia must be overcome, the value of which determined by the time constant τ_{d0} is fairly great.

The method of solving this problem that is adopted in other fields of technology, where inertia forces are to be overcome, consists in applying ultimate powers to the controlling element.

In modern practice, raised powers needed to force excitation are obtained by fitting the excitation systems with forcing groups made for the purpose which allow the excitation voltage to be raised to its maximum value $V_{m\ ceil} = k_f V_{f,nom}$, where k_f is a forcing

multiple; $V_{f,\,nom}$ is a nominal value of the excitation voltage, e.g. its value at the nominal active and reactive load across the generator unit.

It would be correct to keep in mind that 4-fold forcing of excitation used in some Soviet-built generators ($k_f = 4$) corresponds to more than 10-12-fold excitation voltage under no-load running. This is very great a value which permits us to think that during the most essential part of the process the rotor current practically builds up linearly at a rate of k_f/τ_{d0}, e.g. k_f times its growth without forcing.

This circumstance may have a decisive effect on transient, in the system after a short-circuit. Really, an increase in the angle δ when the generator unit is accelerated causes, as known, an increase in the current flow and a corresponding decrease in the voltage across the generator terminals which in turn involves a decrease in the critical angle δ_{cr}. Therefore, the difference $\delta - \delta_{cr}$ diminishes at once in both its components which accelerates the approach of the generator unit to the point of danger. The use of forced excitation allows the terminal voltage of the generators to be faster restored to the required level and, thus, to increase the critical angle. This slowers the approach of the generator unit towards the dangerous point.

This most simple reasoning has been set forth here in order to substantiate the criterion of how the efficiency of forcing excitation depends on the other parameters of the generator unit. It follows from the above that the higher the rate of increasing the angle δ_{cr} due to forced excitation, as compared to the rate of growth of angle δ, the more efficient the excitation forcing. Inasmuch as the rate of growth of angle δ, other things being equal, is unambiguously determined by the generator unit acceleration time constant τ_J, the efficiency criterion K_{fe} may be in such simple form

$$K_{fe} = k_f \tau_J / \tau_{d0} \tag{8.19}$$

Though not strictly substantiated, this criterion is of high importance. It shows, that when assessing the efficiency of excitation forcing for new generator units, they may not be compared to units of earlier types only by the values of k_f and τ_{d0}. Values of τ_J should be included as well. In view if this, for say enclosed units having a 1-2 s acceleration time constant the efficiency of excitation forcing will always be, other things being equal, lower than in the case with hydro units of the conventional type in which τ_J ranges from 5-6 s to 15-16 s.

The efficiency of the excitation system in accomplishing its other important function under post-emergency conditions, e.g. damping power swings in the system, can be assessed in the same manner. To this end, as is known, a pulse in phase quadrature (leading angle δ)

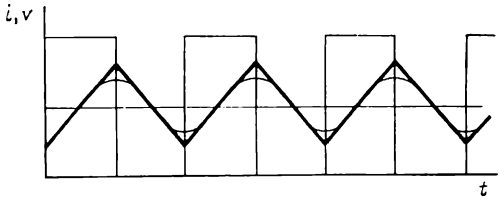


Fig. 8.18

must be injected into the excitation system. In addition, the pulse must be multiplied by the so-called inverse operator $1/W(p)$, where $W(p)$ is a transfer function of the system between the angle sensor or its analogs and the coordinate of the electromagnetic momentum (power).

When intensity of oscillation is great, the resultant waveform goes far beyond $U_{f,nom}$ and the excitation system output pulses will be entirely different in shape—voltage rectangles (meanders) and current triangles (saw-teeth) (Fig. 8.18). It is the fundamental harmonic shown in fine line that produces the searched effect, damping the oscillations. In this, it is clear that the intensity of oscillations is dependent upon the rate of rotor current growth determined by the value of τ_{d0} and also upon the duration of this growth, or, in other words, upon the oscillation period proportional, as known, to the value of $\sqrt{\tau_J}$.

Thus, the criterion of the excitation system efficiency in this event takes the form:

$$K_{de} = k_f \sqrt{\tau_J/\tau_{d0}} \tag{8.20}$$

Hence, this is also the case when the effect efficiency is dependent not only upon k_f, but also upon τ_{d0} and τ_J.

As to the oscillation damping the efficiency of effect may be experimentally determined and quantitatively assessed. To this end use is made of oscillograms of the process in the system after various disturbances. An example is an oscillogram shown in Fig. 8.19.

Assessment of like oscillograms is often made proceeding from the number of cycles discernible in the oscillogram up to the complete attenuation of the process (one, two, three, four cycles, etc.). This assessment, however, is coarse and subjective to certain extent, therefore, attempts are made to improve it. Thus, for instance, considering the oscillation shown in the oscillogram as occurring in a linear system of the second order, the decrement of damping between two adjacent amplitudes is determined as follows:

$$\alpha = \ln (A_1/A_2)/\tau \tag{8.21}$$

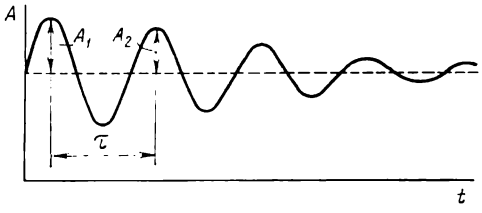


Fig. 8.19

Such an idealization is not quite precise and the decrement α as determined within different pairs of cycles may differ in the value. Practice shows, however, that this difference is commonly small. Besides, use may be made of an average value of α obtained by two or three pairs of cycles.

With the decrement α computed, a generalized factor, e.g. a factor of damping (self-regulation) of the system can be found. Linearizing the equation (8.1) about the point where $\delta = \delta_0$ gives us the formula to determine the coefficient k_s:

$$k_s = 2\tau_J \frac{1}{\tau} \ln \frac{A_1}{A_2} \tag{8.22}$$

In this, the numerical value of k_s obtained from the formula (8.22) illustrates the value of damping force in the machine power units per a unit (100%) of slip. Analyses of a number of transmission systems have made it possible to reveal certain average values of k_s which are about 10-20 for hydraulic-turbine generators having field regulators of a conventional type and 20-40 for hydraulic-turbine generators with forced-control field regulators or regulators with power system stabilizers. Values of 10-30 have been obtained for turbogenerators of modern types. In this event, however, much is dependent upon the performance of the speed governor.

Not only the effect produced by the excitation control accounts for the values mentioned above. Much depends on the asynchronous torque of generators, load characteristics and turbine characteristics. The results of calculations and simulation, however, show that the effect in question is decisive in many instances.

The intensity of damping oscillations by an action on the excitation system is mainly dependent upon the properties of this system. Specifically, the high-speed brushless excitation which practically instantaneously responds to the control signals, will be far more effective than the high-frequency excitation which operates far less effectively. Therefore, emergency control measures of the type described in this chapter are better executed by exciters of the former type.

Practically the action on excitation is the only means of those considered herein that can have both signs. This can be effected only through a brushless exciter furnished with inverter groups. If that is the case, power will be not only delivered to the rotor circuit, but also withdrawn from it, and the amplitude of electromagnetic momentum alternation for damping oscillations will be essentially higher.

Let considerations be given to the *specific features of this kind of control.* Control of the excitation forcing with a view to maintaining the voltage at the required level is implemented by the relay functioning in response to a short circuit, the corresponding signal being sustained during several seconds after the fault has been cleared. The control of the excitation with a view to damping oscillations may be a relay type also. In the home-made systems, however, such control is accomplished usually by forced control regulators. The pulses from these regulators have an amplitude sufficient to consider them forced. If that is the case, in lieu of derivatives of the power angle use is commonly made of the values the system frequency deviates from its initial value.

New methods of control. Today other methods to control electromechanical transients under emergency conditions in power systems are under development. Among others most promising are such as partial dewatering of the scroll casing of a hydropower plant and the use of the so called asynchronized generators.

Partial dewatering of the scroll casing of hydraulic turbines. Unlike the control of steam turbines, the control of hydraulic turbines is a slow process and cannot be a means of direct action on transients under emergency conditions in power systems. Nevertheless, the conditions under which a hydraulic power plant operates in a system often make this control necessary, and the above-described techniques (GR and the like) are not always efficient and convenient in service. In view of this, research and development work on devices for short-time controllable reduction of mechanical momentum of the turbine under emergency conditions, utilizing negative water hammer, is conducted in this country during recent years.

Attention should be given to the method illustrated in Fig. 8.20. Its principle of operation is as follows. The end of the penstock, directly before the scroll casing is furnished with reservoir *1* normally filled with compressed air at a pressure above the water pressure at the turbine scroll casing. The top cover of the reservoir has solenoid-operated valve *2* which responds to the control pulses produced by the emergency control equipment at fault. As this happens, the solenoid valve opens to release compressed air and admit water into the reservoir. As a result, the scroll casing of the turbine becomes partially dewatered and the turbine power drops respectively.

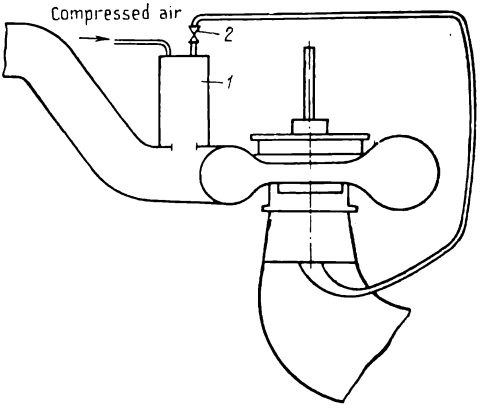


Fig. 8.20

To enhance the effect produced, the compressed air from the reservoir is directed under the draft tube of the turbine. This upsets vacuum in the draft tube and still more reduces the mechanical torque of the unit.

The pattern of mechanical power reduction is much the same as the mechanical power reduction caused by FTC. This is proved by curves shown in Fig. 8.21 which have been obtained on an experimental installation at various durations of control pulses ($\Delta t_1, \ldots$ $\ldots, \Delta t_4$) applied to the solenoid valve.

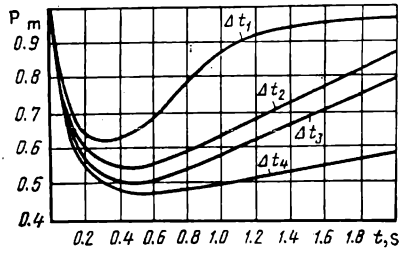


Fig. 8.21

Practical use of this method involves certain modifications of the hydraulic power units. In addition, use should be made of quick-acting solenoid valves designed for large flow rates of compressed air. There is also need for sources of compressed air, such as powerful compressor installations. With all these requirements properly satisfied, the emergency control technology will receive one more control method possessing the FTC properties, but suitable to hydraulic turbines.

Use of machines with two windings on the rotor. This method of controlling electromechanical transients in power systems which is also still under research and development may be thought of as a continuation and further development of the emergency control method through the excitation control. This method works as follows.

The rotor of a synchronous machine has two, but not one, windings whose axes are in quadrature with each other. Each of the windings is at its own field voltage V_{fd} and V_{fq}. Then, as shown in Fig. 8.22, the resulting field flow F of the machine represents a vector sum of the fluxes of the above-mentioned windings (F_d and F_q). Varying the magnitude and direction of the fluxes in each of the windings, the vector of the resulting flux may be turned into any required position.

This basic principle can be realized in different variants. The most simple of these consists in opposing an increase in the unit rotor speed dangerous from the stability point of view by shifting the resulting flux in the direction opposite to the rotor rotation. To this end, the fluxes in each winding should be changed in time as follows:

$$F_q = F \cos \delta; \qquad F_d = F \sin \delta \tag{8.23}$$

where δ is an angle between the winding axis and stator flux axis.

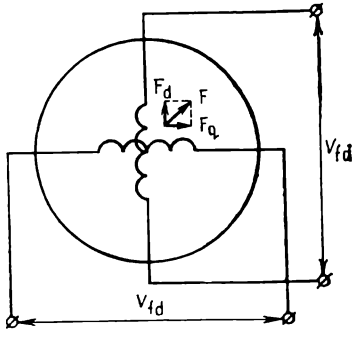


Fig. 8.22

A similar principle of shifting the fluxes may be utilized when a machine under steady-state conditions needs to have a rotor angular speed other than that in step ω_s, e.g. has a certain slip s with regard to the stator flux. If that is the case, the above-given expressions may be rewritten in the following form:

$$F_q = F \cos s\omega_s t; \qquad F_d = F \sin S\omega_s t \tag{8.24}$$

A machine adapted to operation under these conditions is called an *asynchronized synchronous machine.*

Under steady-state operating conditions it is always possible to introduce a constant advance of the pulse of the rotor slip ring voltage with regard to the required flux, thus creating a compensation of lag associated with the rotor inductance. Such a lead can be introduced at small oscillations as well. Under disturbances of a short-circuit type, however, the value of this lead should abruptly change, and the synchronous speed of the resulting flux can be maintained only by applying large powers to the excitation system, about the same as the power values needed to obtain a high damping factor.

In this event it should be kept in mind that the rotor slip rings of the asynchronized asynchronous machine (ASM) are at a voltage

supplied from a special converter installation generating sine pulses.

Under short-circuit conditions this installation cannot develop a sufficient power and is capable of satisfying the above requirements only to a fairly less extent.

The operating principle of the asynchronized asynchronous machine is carried out under heavy disturbances with certain difficulties which are overcome by techniques suggested for control under emergency conditions. If that is the case, the converter installations stop generating sine pulses and change over to mode of exciting a conventional synchronous machine, with the use of forcing to a full ceiling voltage.

To some extent the sign choice (voltage sign) controls the resulting flux by shifting it in the direction opposite to the direction of drift. As the case is with the conventional excitation forcing, the efficiency of this control, however, is dependent on the relationship $k_f \tau_J/\tau_{d0}$ and is relatively low at the conventional parameters of modern units. In view of this, the main effect of the above-discussed actions consists in their combination. Under pre-emergency conditions the machine operates as an ASM with a certain negative slip s_0 and under emergency conditions it is changed over to the operation of a conventional synchronous machine.

The resultant process is as follows. The unit rotor accelerates, but this acceleration is of no hazard for some period of time, since it only compensates for the negative slip s_0. After the short-circuit has been cleared, the machine reassumes the operation of an ASM.

Therefore, this type machine may be treated as having a certain additional margin of stability measured by the possibility of increasing the short-circuit clearing time Δt_{sc} in compliance with the following coarse relationship

$$\Delta t_{sc} \approx \frac{\tau_J}{\Delta P_{sc}} |s_0| \tag{8.25}$$

where ΔP_{sc} is a power drop because of a short circuit. A time gain from this indirect factor is about 0.05-0.07 s. Remember, however, that creating an ASM calls for a machine rotor of intricate design to fit two (or even three) windings and a complicated excitation system furnished with reversible thyristor converters rated for active power $S_0 P_0$ and reactive power determined by the parameters of the machine and operating conditions. The machine will cost more, but may be sometimes advisable.

An example in this respect may be flood hydropower plants which must generate as much power as practicable. However, emergency disturbances to the stability in this case are intolerable either.

In addition to the use of the discussed principles of utilizing machines with two rotor windings, there are other offers. An example

is an objection to utilize ASM operation under the pre-fault conditions, organizing the flux control only under the short-circuit conditions (the so-called phase control). In this event too the effect will be dependent mainly on the $k_f\tau_J/\tau_{d0}$ ratio.

Now let considerations be given to *specific features of these kinds of control.* Inasmuch as the effect of partial dewatering of the scroll casing of hydraulic turbines is similar to the effect produced by FTC, the technique of working outcontrol modes herein may be similar either. With the use of asynchronized synchronous machines, the control under steady-state conditions differs from that under transients.

The purpose of the control under steady-state conditions is to provide for stability of unit operation at the required values of rotor slip relative to the network voltage vector. To this end the terminal voltage of each rotor winding may be controlled as follows:

$$\begin{aligned} V_{fq} &= (1 + k_e)(\alpha_0 + \alpha_1 s)\cos(\delta + A) - k_e e_q \\ V_{fd} &= (1 + k_e)(\alpha_0 + \alpha_1 s)\sin(\delta + A) - k_e e_d \end{aligned} \qquad (8.26)$$

where k_e and α_1 are gain factors; α_0 and A are constants dependent on the unit operating conditions; e_q and e_d are emfs proportional to the current flow in the circuit of each rotor winding.

These principles provide for the maintenance of the specified operating conditions of a unit given in terms of the displacement angle δ of its rotor and slip s and also the formation of stabilizing rotor current feedback (components $k_e e_q$ and $k_e e_d$).

Under transient conditions, when the machine changes over to synchronous generator operation the control is accomplished as follows. The first moment a full (ceiling) rotor voltage is applied to each winding and the signs of U_{fq} and U_{fd} are chosen proceeding from the angular position of the rotor relative to the network voltage U_n. Next, the excitation is controlled in compliance with the expression (8.23).

Power limitation. Under the conditions, when the post-emergency limit of the transmitted power becomes lower than the transmission line loads under pre-fault conditions, the fast (emergency) turbine control (FTC) is supported by one more emergency control measure—by emergency power limitation (EPL) utilized (in place of GR) to restore the steady-state stability conditions. The purpose of the EPL is to return the turbine output power upon completion of the FTC process to a new value P_m^{II} rather than to its initial value P_m^{I}, P_m^{II} differing from P_m^{I} by a specified value ΔP_{ms}.

The value of ΔP_{ms} is defined by the minimum power the turbogenerators can carry without upsetting the operating conditions of the unit boiler. This power is dependent on the type of equipment and the fuel burned at the power plant. For modern power units

having supercritical steam conditions and straight-through boilers, this power limit is (in %% of the unit nominal power) 70—when operating on pulverized coal fuel, 50—when operating on boiler oil, and 30—when operating on a gas. Accordingly, the maximum possible levels of post-emergency unloading amounts (with the pre-fault power being 100%) will be 30, 50 and 70%. At a reduced pre-emergency load these amounts will be still greater, for which reason the sole EPL in certain cases turns out to be insufficient and is assisted by additional GR.

The emergency power limitation is performed concurrently with forced unloading of the turbine to respond to transient unstability. A large amount of the unit power reduction in the period of such unloading provides a certain time reserve (of the order of 3-5 s) for the emergency limitation. As a result, one of the possibilities of conducting the indicated operation consists in that the unit SC is caused to spin at a raised speed in the "lower" direction during a certain period of time in proportion to ΔP_{ms}.

The EPL method was implemented at certain power plants for which purpose use was made of SC high-speed (earlier intended only for winding-up the turbine emergency governor) available on the machine built by the Leningrad Metal Works). However, the SC is coupled with the turbine governor through a friction clutch in which a slip occurs leading to a large error in the EPL (up to 30% of ΔP_{ms}). In view of this, today more perfect schemes for emergency power limitation are introduced into practice. The turbine control in these schemes, when the process is initiated, is effected through the EHC. In that, the signal on the governor must be changed over (substituted), through SC.

A simplest aid of emergency power limitation is the so-called "open loop limiter" from which a pulse is applied to the EHC input in proportion to the specified reduction of mechanical power ΔP_{ms}. After this a mutually synchronized operation may be accomplished in order to gradually remove the pulse from the EHC and transfer it to the SC. These limiters were used for a number of years in one of power plants. However, their accuracy is insufficient and they are replaced with limiters having a controllable value closed loop.

The first limiter of this type was a post-emergency unloading unit which makes it possible to make up through an EHC a unit electric power closed operating (through a diode) in one direction only to reduce the turbine power.

Another circuit finds its application in the so-called "coarse-fine" limiters. These limiters preserve an open loop to deliver a signal proportional to ΔP_{ms}, and also utilize a closed loop allowing correction to the performance of the open loop and upkeep the value under control at the specified level. Applied to the input of the open loop of the limiter is a setting ΔP_{ms} for which the unloading

should be carried out. Such a signal is often known as a signal in the form of BY. The signal P_{ms}^{II} to which the unloading should be carried out is applied to the input of the closed loop. This signal is called a signal in the form of TO.

The problem of shaping and handling the above-mentioned signals brings about the necessity of creating a whole system of emergency power limitation (EPLS) comprising system, plant and unit parts. The system part of EPLS stores the source data on the transmission line load P^{I} and determines the load transmission capability of the trunk lines under any post-emergency conditions. The result is either a signal about the required (specified) level of plant unloading ΔP_{ps}, signal about the specified level of plant post-emergency load P_{ps}^{II}, or both signals together.

The master station controller distributes the received setting (assignment) among the power plant units, allowing for their control ranges (the power values determining these ranges are set by personnel manually for each unit individually), and also determines the necessity and amount of additional unloading by the GR method.

The signals from master station controller are applied to the unit EPL devices which contain an open loop and a closed loop. If that is the case, two variants of closed loop are possible for a unit electrical load operation and for a unit mechanical power operation. In order to get the difference between these variants clear, write the equation of the unit motion in the form of swing equation:

$$\frac{\tau_J}{\omega_c}\frac{d^2\delta}{dt^2}+k_s\frac{d\delta}{dt}+P_{12}\sin\delta=P_m$$

where τ_J is an acceleration constant; ω_c is the synchronous speed; δ is a displacement angle of the unit rotor; k_s is a self-regulation factor; P_{12} is the maximum of the power angle curve; P_m is the mechanical power (on the unit shaft).

Then linearize this equation about a certain point δ_0 and rewrite it in the form of a transfer function between the mechanical P_m and electrical P_e powers of the unit:

$$W(p)=\frac{P_e(p)}{P_m(p)}=\frac{1}{ap^2+bp+1}$$

where $\alpha=\tau_J/(\omega_c P_{12}\cos\delta_0)$; $b=k_s/(\omega_c P_{12}\cos\delta_0)$.

Thus, closed system which responds to the electric power differs from closed system using mechanical power by one more (oscillatory) element. More than that, in the mechanical power control the value under control is dependent only on the condition of the controlled equipment and the system is self-contained. Whereas in the electrical power control the value under control is dependent on the processes occurring in the electrical part of the power system, as well as on the turbine conditions and the system is coupled.

Independence is a valuable property of any control system, and now endeavours are made to create P_m - closed limiters. Direct measurements of P_m are impossible, and an indirect method is used to determine it approximately by the sum of electric power and unit acceleration multiplied by the unit acceleration constant.

At the same time another P_m-closed limiter has been built and tested in a power system. A simple closure of the system is impossible in this case, as resonance phenomena intrinsic in the oscillatory element can make the system unstable. In order to prevent this, one more series element of corrective action is introduced into the control channel with the transfer function

$$W_c(p) = (1 + \alpha Tp)/(1 + Tp)$$

For typical operating conditions of 300 MW turbo-generators operating through a trunk line into a powerful network, the values $T = 5$ s and $\alpha = 0.1$ produce a critical permissible gain in a closed loop, equal to 20-30, and at a practically acceptable gain $k = 20$ an error on account of the system static slope curve (system speed regulation) does not exceed 5 per cent.

Note that a P_e-closed limiter can be changed into a transmission angle regulator by merely replacing the transducer. Under post-emergency conditions, when the transmission line voltage oscillates, such a regulator turns out to be more efficient than one controlling power, while the technique of obtaining a voltage vector of the opposite end of the transmission line (which is necessary for angle measurements) is now hardly a practical problem.

As it becomes clear, today not only is the turbine power to be rapidly reduced, but it is to be quickly increased. This applied to underloaded units in a deficit part of the power system which are advisable to be quickly loaded under corresponding emergency conditions in the power system. Devices used to satisfy this objective are similar to the emergency control and power limitations (only with reversal of the action sign).

8.7. Criteria and Algorithms of Transients Control Methods

The modern state of emergency control technology features a conflict between the continuous nature of electromechanical transient processes in power systems and discrete (discontinuous) action (most often single-action) of control devices. This is because of high intensity of processes under control required forced actions and specific features of the facilities used for the purpose which are single-actions in their nature. Because of these circumstances the structure of emergency control devices becomes far from the structure commonly used to control continuous processes, i.e. regulators and in many

aspects approaches the structure of protective relaying and line automatic devices.

Another reason for this similarity is in that the same apparatus and methods of measurement are used in relay protection and emergency control schemes. In fact, with the electromechanical transients in power systems considered from their theory point of view, the basic parameters governing process behaviour are the generator displacement angle δ, slip s, and acceleration ds/dt.

However, measurement of these parameters requires fairly complicated apparatus. More than that, the measurement of the displacement angle and its derivatives commonly calls for telecast of the voltage vector from one part of the system to another. These apparatus have not yet found wide applications and the parameters of relative motion of system parts under emergency conditions are interpreted through their analogs—power, current, frequent, etc. Moreover measurements are often made by means of relays employed in protective relaying.

Another factor drawing emergency control schemes and protective relaying closer is the reliability requirements sometimes treated even to the detriment of the control quality. Practice has shown that, if the performance of the automatic control devices under emergency conditions turns out to be somewhat improper, i.e. more than necessary generators are tripped, or unnecessary sectioning of the system is performed, consumers' loss will be far less, than the case would be with the complete failure of the automatic control system pregnant with a heavy failure of the entire power network.

Faults in power systems may involve intensive electromagnetic and other interference, for which reason the automatic control gear must be immune to noise. All methods and facilities utilized in the emergency control are subject to thorough reliability and noise immunity analyses with the choice of those which completely satisfy these reliability requirements. The criterion of reliability generally implies a minimum number of components, absence of telecast means, etc., whilst the criterion of interference immunity—a minimum number of operations performed by the automatic control facilities directly at the instant of fault and simplicity of these operations.

The third factor is a requirement for high speed of response. The faster is the schemes operation at faults, the less is the required intensity at actions, and the better is the possibility of sustaining the network stability.

The last factor, that makes the automatic control techniques under consideration dissimilar to apparatus of the regulator type and brings it closer to devices of another class, consists in the peculiarity of the problem to be solved by these techniques with a view to bringing the controlled system into an area, rather than to a point. This is accounted for by the existence of certain margins of short-time

deviations in the parameters of power system operating conditions from ratings and by the presence of a true equilibrium state attraction zone in the system. Returning to this zone means that to sustain the transient stability requires no additional actions. An example of such zones may be a space within the boundary phase trajectories (see Fig. 8.9). More than that, in actual power systems these zones are formed in addition to the synchronizing forces still by asynchronous momentum of generators, self-regulation of turbines, self-regulation of loads, and also by the speed governors and excitation regulators (especially forced action regulators), which results in expansion of such zones (see Fig. 8.10). Therefore, with proper pre-fault operating conditions of power systems and correct choice of steady-state relations for post-emergency performance, sizes of such zones are always finite, and sometimes considerable, so that one and the same control gear may be utilized under different disturbances. The latter concept connotes the fact that the associated facilities may be fairly coarse and thus reliable in service.

Giving these reasonings, we should remember that with small permissible areas, the problems facing the emergency control schemes have to be tackled with the aid of fairly "fine" facilities. However, a tendency in practice is to avoid such cases ("bottle-necks" of permissible areas) and they are considered herein as hypothetical. Whereas the real power systems mainly use as yet most simple automatic control facilities effectively carrying out rather important tasks of providing reliable performance of power systems.

At the same time there is another tendency. With the structure of power systems becoming more complicated, growth of the number of large powerful stations and extended power transmission lines, we have to take into account a great number of factors, when selecting emergency control commands, including information coming from many installations under control far distant from one another. If that is the case, the same information may be used for diverse purposes, which makes us unite the output circuits of information sources and subject the information to complex logical handling and sometimes to computation operations. To this end, research, development and implementation efforts are made to customize perfectly new facilities known as *complex automatic control devices* including powerful means of information processing, digital computers included.

Simple devices of automatic control being commonly local, the complex devices are thought of as related to the level of power utility, or so-called area of emergency control. Next, if necessary, are devices of lower levels covering power plants and units. Later it may become practicable to include emergency control schemes directly into the automatic dispatching control system (ADCS). Then it will be a level of power systems or power grids.

To assess the modern tendencies in the progress of emergency control facilities consider three problems:

(1) Use of most simple out-of-step protections system sectioning (SS) and asynchronous running control (ARAC);

(2) Use of central automatic control equipment incorporating a digital computer;

(3) Use of the above mentioned emergency control schemes in conjunction with ADCS.

System out-of-step protection. Automatic devices intended to section the power system during the very first cycle of asynchronous operation are provided in two cases.

The first case covers the so-called weak tie lines which interconnect large systems or pools exchanging power during hours of excessive power in one system and lack of power in another system. Amount of power exchange is commonly small and when stability of such a line is lost, it is advisable to open it and as quick as possible, as each system may have several directions of power exchange and the result may be multifrequency asynchronous operation.

The other case includes strong ties on which asynchronous operation is intolerable because of a high overcurrent and it is good practice to break the tie line before the current reaches its maximum, i.e. during the first half cycle. Therefore, it is desirable that the automatic devices in both cases function just on the risk of instability. The sooner the automatic control devices are to operate, the larger is the amount of information to be collected by the automatic control system, and the more a priori assumptions should be taken. To see this clearly, consider three types of devices. These are steady-state, transient, and predicting control devices.

The steady-state control devices. By this name is meant a class of devices in design of which all opinions connected with the intricate transient nature of the process are neglected, and the designer orients himself only towards the value of power angle δ whose approach to a certain value is considered to be a symptom of a risk of an instability. A direct measurement of the angle is difficult, for which reason use is commonly made of its analogs, among which the most important is the transmission current I.

The use of current I as an analog of the angle δ is convenient since in this case conventional current relays widely used in practice are utilized as emergency control devices. Provision should be made to prevent the devices from functioning under short-circuit conditions. To this end, three relays are installed, their coils being connected to three different phases (A, B and C) and their contacts being connected in series. Then under asymmetrical fault conditions at least one relay will not pick up, while symmetric faults are probable, but little.

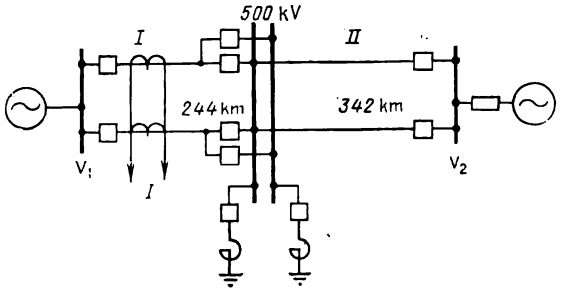


Fig. 8.23

Having presented the line in the form of a two-port network with self-impedance x_{11}, mutual impedance x_{12}, and ratio $D = x_{12}/x_{11}$, assuming an equality of end voltages $V_1 = V_2 \approx V$, and neglecting losses we obtain current I versus angle δ.

$$I = \frac{V}{x_{11}} \sqrt{\frac{1}{D^2} - \frac{2}{D} \cos \delta + 1} \qquad (8.27)$$

This relationship allows us to assess an error of this type of out-of-step protection which appears because of changes in the transmission system diagram and due to variations in voltage V. This assessment is made for an actual power transmission line, rated for 500 kV, whose diagram is shown in Fig. 8.23. For the parameters of the transmission line with changes in its composition see Table 8.1.

Table 8.1

No. of diagram	Transmission line composition	Parameters		
		x_{11}, ohm	x_{12}, ohm	$D = \frac{x_{12}}{x_{11}}$
I	Complete line	144	128	0.89
II	Breakers *A* and *B* are opened	172	162	0.94
III	Breakers *A*, *B*, *C* and *D* are opend	198	199	1.01

The I (δ) relationships for the given transmission line are shown in Fig. 8.24, in which each of the curves corresponds to certain composition of the transmission line (*I*, *II* and *III*), and the shaded zones depict the effect of voltage variations within $\pm$ 5 per cent. The dash lines in the diagram indicate possible current (I_{or}) setting and associated angles δ_{orI}, δ_{orII}, and δ_{orIII} the difference between which turns to be fairly large.

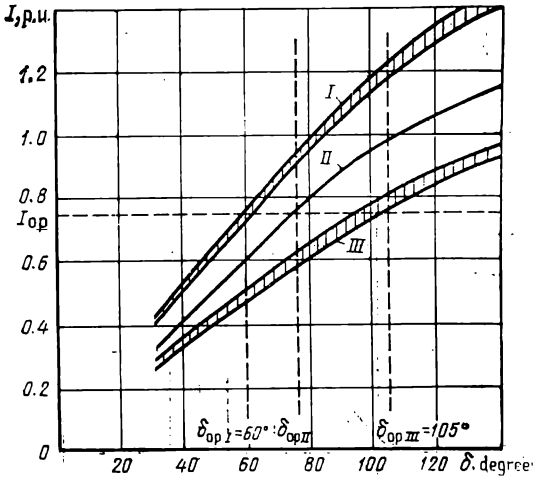


Fig. 8.24

There is still another method of using current to obtain an analog of a power angle. It consists in joint use of a phase-meter and the scheme, a model of a transmission line (reactance x_m representing line self-impedance on a certain scale x_{11}), and allows us to customize the following expression

$$\dot{V}_2 = \dot{V}_1 - \dot{I}x_{11} \tag{8.28}$$

i.e. to obtain a certain voltage vector in the place of device installation (at the beginning of the line). With a complete similitude between the line and its model ($k = x_m/x_{11} = 1$), this vector coincides with the vector of the receiving end voltage $\dot{V}_2$ of the line, otherwise the latter vector differs from the former one and is angle-shifted relative to $\dot{V}_1$:

$$\delta_m = \arctan \frac{(k_m/D) \sin \delta}{(k_m/D) \cos \delta + 1} \tag{8.29}$$

For this method of measuring angle δ calculations were made similar to the above-mentioned. Their results are shown in Fig. 8.25. They testify to that the absence of dependency of the measurement results upon the voltage and other causes contribute to the fact that the spread of protection operating points essentially decreases when the transmission line operating conditions vary. This is why scheme with line model is thought of as more perfect and is customized now at some power utilities.

The considered type devices require in their operation not much information (sometimes even changes in he composition of the

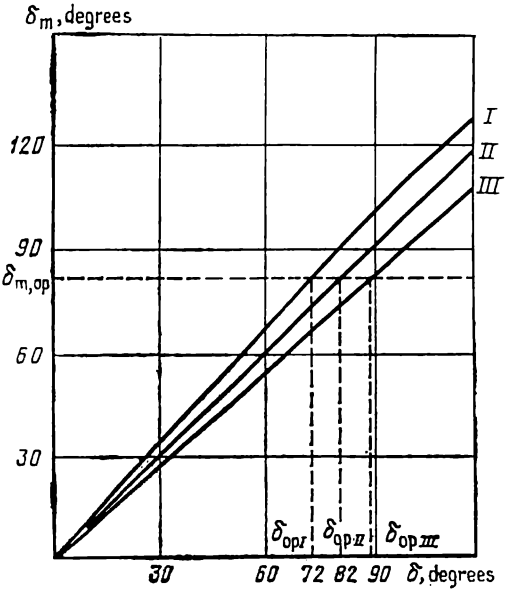


Fig. 8.25

transmission line may be neglected). However, their operation is very delayed. They function only after a material change in the angle. More than that, inasmuch as the critical value of the power angle is herein unknown, the correct discriminating performance of the automatic control devices is fully guaranteed only by a setting of $\delta_{op} \geqslant \pi$.

The transient state control devices. These are devices that allow us to determine when the system goes over to the descending branch of the power curve and when the angle passes its critical value δ_{cr}. To determine this, checks should be made to see whether the following three criteria are concurrently fulfilled:

$$dP/dt < 0; \quad d\delta/dt > 0; \quad P < P_0 \tag{8.30}$$

where P is the current value of the transmission line load; P_0 is the initial (pre-fault) value of the transmission line load.

It is apparent that the given device can detect an actual risk of stability disturbances far earlier than the above-described device. It however needs much more data comprising power values P and P_0 (the latter as a stored value), and also determination of the sign of the derivative $d\delta/dt$ for which purpose the angle δ should be known.

The predicting control devices. Using the basic postulates of power systems, stability theory, the nature (stable or unstable) of a transient may be determined (predicted) still during the transient. One

of the methods of this prediction consists in comparing the current value of slip with its boundary value:

$$s_b = \sqrt{2\frac{\omega_s}{T_J}[P_0(\delta - \delta_{cr}) + P_{12}(\cos\delta - \cos\delta_{cr})]} \qquad (8.31)$$

where ω_s is a synchronous speed; T_J is an acceleration constant; δ_{cr} is a critical value of the transmission angle that is determined as $\delta_{cr} = \pi - \delta_0$ (herein δ_0 is a pre-fault value of the angle); P_{12} is a maximum value of power angle curve under post-emergency conditions.

This expression shows that to operate device based on it needs not only data on the operating conditions parameters, but also on the parameters (constants) of the transmission line determined by its composition. In this, the instant of revealing the risk of instability is determined at the instant, the system motion path crosses the boundary phase trajectory, i.e. precedes what has been obtained by the previous methods, but is materially shifted as compared to the instant a short circuit occurs.

There is a method of earliest detection (prediction) of such risk that almost coincides in time with the instant a short circuit occurs, but, in addition, this method calls for determining the value of power drop ΔP_{sc} and making a priori assumptions with respect to the duration of short circuit. This method is given by the expression to assess a critical permissible power drop ΔP_{sccr}:

$$\Delta P_{sccr} = \frac{P_0\tau_{sc}}{2}(1 - P_{12}) - \sqrt{\frac{P_0^2\tau_{sc}^2}{2}(1 - P_{12})^2 - \sqrt{1 - P_0}\left(\sqrt{1 + P_0} - \frac{\sqrt{2}P_0}{P_{12}}\right)} \qquad (8.32)$$

where τ_{sc} is modified time of short circuit; $\tau_{sc} = \Delta t_{sc}\sqrt{\frac{P_{12}\omega_s}{\tau_j}}$; P_{12} is the amplitude of the power angle curve under post-emergency conditions.

This expression is obtained in an assumption that ΔP_{sc} remains constant during the entire time Δt_{sc} and with the use of an approximate transformation of the associated trigonometrical functions. In view of this, it yields more or less accurate results only when the short circuit takes 0.12-0.2 s.

The composition of this expression testifies to that a most early recognition of the risk of a stability loss requires a largest amount of information. In this, part of the information is a priori. This part includes the magnitude Δt_{sc} (which is predicted should the main protective gear function and the back-up protection may operate as well) and the magnitude ΔP_{sc} (which is considered unchanged, though a change over from one kind of short circuit to another may take place).

Therefore, if the protection under consideration must provide qualitative performance, then even most simple devices require a fairly large amount of information covering both the emergency state of the power system and its pre-fault conditions (an example is the magnitude P_0). Besides, often a necessity arises to give this information relatively complicated processing.

Out-of-step protection with cycle counter. Being installed on power transmission lines in which asynchronous cycles are tolerable, this protection must break tie lines, when asynchronous cycles persist for a too long period of time, but at the same time it must be capable of discriminating between asynchronous cycles and synchronous wings and the like. To provide this capability, use is commonly made of two symptoms of asynchronous operation. These are a periodic alternation of the active power sign and periodic increasing of the current flow in the transmission line. The first of these symptoms is evident. If a unit is out of step, its voltage vector continuously revolves about the mains voltage and the power sign of this unit corresponds now to generator now to motor-mode. This symptom however is not enough, since similar alternating of the power sign with entering motor mode may also result from heavy synchronous swings. That is why, use is made of the other symptom—a current flow which, when the voltage vector crosses the boundary between quadratures II and III, will be far higher than when this vector crosses the boundary between quadratures I and IV.

Thus, comparing the moments, the sign of power and current changes, we can determine whether the vector of voltage passes in sequence all the four quadratures, i.e. out-of-step operation, or it periodically crosses the boundary between quadratures I and IV, i.e. heavy synchronous swings. To this end use is made of specific relay logic.

The devices under consideration commonly incorporate one current and one power relays, which makes the circuit asymmetric, and under asymmetric fault conditions such random combinations of current magnitude and power sign that will be recognized by the device as asynchronous cycles. When use is made of auto-reclosure modes, such combinations may occur several times. In view of this, the device is generally allowed to operate only after recording a marked number of such cycles (3, . . ., 5) of current and power changes. And this requires that a cycle counter be utilized in the device which makes its logic still more complicated.

It is also of importance that the device prevents the tie-line from premature opening and does not hinder with self-resynchronization because of the effects of speed governors and other factors). This objective is satisfied as follows. Counting cycles of power sign and current magnitude change detects asynchronous operation. After this the specified time delay Δt elapses, and the cycle counting will

start again. If this counting shows that the asynchronous running is not yet terminated, a command is sent to open the tie-line.

Central emergency control devices. It is good to start the discussion of central automatic control devices with an analysis of problems that face them. In most cases these problems consist in maintenance of transient stability. However, a wide approach to this proposition is possible (and already becomes true), i.e. monitoring the power system operating conditions by any set of state variables. If that is the case, the functions of the emergency control scheme are to assess the S_2 (t) vector of the system post-emergency state formed by imposing the disturbance vector $\mathbf{V}$ (t) on the pre-fault state vector S_0, choose a point of application, type and intensity of the required actions shape on this basis actual control commands $\mathbf{U}$ (t), $\mathbf{U}$ as before is considered a vector, since to perform all the functions of the automatic control (or just one its function) may call for several diverse actions with different points of their application.

Therefore, the problem facing the emergency control in this case may be mathematically formulated as finding the relationship

$$\mathbf{U}(t) = F(S_2) \qquad (8.33)$$

Such a problem facing many automatic control devices of different types is commonly solved through direct monitoring of the state of S_2. There is a peculiarity however. This state is not determined by the essential elements of automatic control. They only predict directly at the moment of disturbance on the basis of the following relationship:

$$\mathbf{U}(t) = F[S_0;\ \mathbf{V}(t)|_{t=0}] \qquad (8.34)$$

Possibilities of this kind are connected with the fact that disturbances in power systems develop in time absolutely in a similar manner. Thus, for example, duration of a short circuit at some point of the system is determined by the time of operation of the protection gear, and with the position of short-circuit known, the configuration of the system after the short-circuit has been cleared, can be foreseen. At the same time the possibility of generating U without waiting for the process to develop allows the system speed of response to be increased, and thus to cope with a disturbance producing a less intensive action, i.e. this is a positive factor.

Such a method however has obvious disadvantages too. These are impossibility of taking into consideration changes in the course of fault, failure of the main protection gear (functioning of a back-up protection gear), and emergency conditions under the cascading faults (the scourage of modern power system). When use is made of the automatic control under consideration, such faults are liquidated mainly by sectioning the system, i.e. by the out-of-step protection which backs up in this respect the main emergence control. This solu-

tion however may be considered only as forced which encourages the further R. and D. efforts to tackle the problem.

The automatic control devices of this type have one more peculiarity that manifests itself most obviously in searching for control actions providing the required dynamics of the process. The time available for searching control actions is commonly fairly small and in the absence of superhigh speed computers they can be obtained only by retrival from a storage device containing the results of preliminary off-line computations. At first sight such a system is awkward and difficult to put into practice. In this case, however helpful is the specific feature of the emergency control schemes which are to bring the power system to an area rather than to a point. This makes the control rough and the block of data stored in the system memory comparatively small.

In the past, when the sections of the power system under control of one device were developed, but not highly, a required design table could be stored even in relay-contact circuits, including switches or switch-boards made for the purpose. Today this objective may be attained through the use of digital computers which can at the same time carry out computations of steady-state relations (in which case the amount of computations is far less, hence the requirements for speed of operation not so high).

In this way the modern practice of emergency control has attained the techniques of satisfying requirements for high speed of operation under complicated conditions, while the properties of reliability and interference immunity are taken into consideration in creating fault detectors by which are meant apparatus like signal contacts of circuit breakers, output relays of protection gear devices and special relays to register disappearance of current in the line, power drop magnitude and the like. All these apparatuses have a common feature: they must be suited for performance under complex conditions occurring because of faults in power systems and be capable of giving enough information about $\mathbf{V}(t)\,|_{t=0}$ merely by closing or opening the contacts.

Referring to the diagram in Fig. 8.1, one can ascertain that this possibility is anything but hypothetical. In this case, the operation of protection gear uniquely indicates a fault, i.e. gives complete information about the scheme change in transition from the pre- to after-emergency conditions.

With a view to making them more dependable, fault detectors are often duplicated, while in more complicated cases, when the nature of a fault can be identified only by a set of symptoms, they are connected to specific fault detecting circuits which logically process the signals from the fault detector (determine whether the signals do or do not coincide). In this manner the number of the fault detectors involved, N_i ($i = 1, 2, \ldots, n$) or the number of the

fault detectors circuit (the number of such elements or circuits being finite) uniquely determines $\mathbf{V}(t)|_{t=0}$, i.e. there is a relationship

$$N_i = \mathbf{V}(t)|_{t=0} \tag{8.35}$$

From the mathematical point of view it means that all possible disturbances in power systems are substituted for (approximated) by a finite set of disturbance vectors which is often not large. Such an approximation is fairly rough. However, it allows the performance of automatic control to be reduced to generation of noise-proof signals of the "yes—no" type. These signals readily lend themselves to telecast, for which purpose special devices of improved reliability are developed.

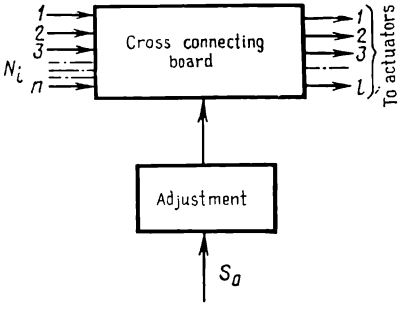


Fig. 8.26

Hence, with a set of fault detectors covering all faults considered in the design of a given system, one term of the expression (8.34) may be thought of as found and in order to search the control action we have only to determine the other its term $\mathbf{S}_0$. This operation is carried out by *Automatic Action Adjuster* (AAA)—a device (Fig. 8.26) comprising two essentials: a specific cross-connecting board to which conductors are laid from the fault detectors and actuating elements of the emergency control gear and an adjustment control device which in respose to $\mathbf{S}_0$ can change (adjust) signal paths between the above-mentioned elements.

The operation of the AAA allows us to make an action on the power system at fault dependent not only upon $\mathbf{V}$, but also upon $\mathbf{S}_0$, i.e. to satisfy the relationship (8.34). In this case, however, $\mathbf{U}$ is also approximated by the finite (discrete) set of control actions. Note that in this case the earlier mentioned propositions regarding the rough action of the automatic control gear and high requirements to its reliability may be supplemented by one more notion that almost all actions implemented by emergency control, are discrete in nature and fairly coarse.

There is already a number of relay-AAA in which all information about the pre-fault condition of the system confines itself to the value of active power P_0 and data on the transmission line scheme which may be either normal, i.e. complete, or under outage condition, i.e. with one circuit of it open. If that is the case, active power (P_0) measurements are made by the so-called analog-relay converter, i.e. by a set of power relays having logic to store pre-fault

state of the contacts and furnished with an appropriate number of relay-repeaters P_{0i}.

Let us consider now the operating principle of such AAA (Fig. 8.27).

Where *HD*—fault detectors responding to faults in power systems;

P—pulses fed to the actuating elements and providing required effects on the power system when the faults occur;

O. and N. w/o subscripts—switches responding to signals (pulses) on outage (O) and normal (N) mode of operation of the transmission line;

CB— cross-connecting boards on which the required relations among the type of fault, pre-fault condition of the system and required effect are set manually.

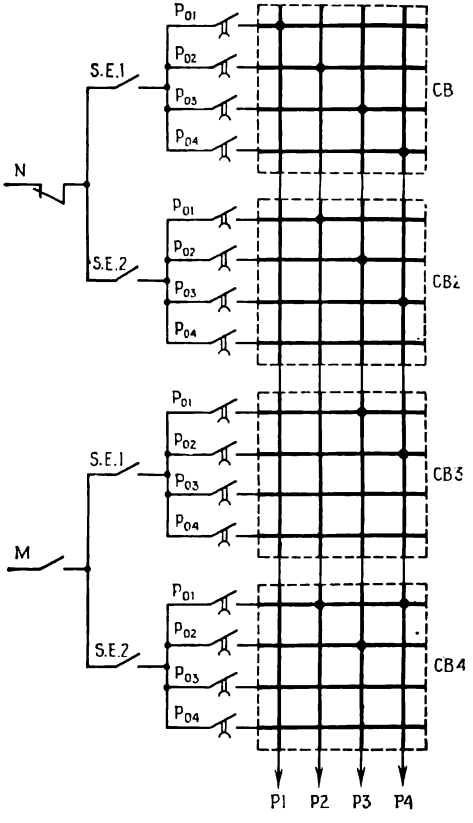


Fig. 8.27

The diagram in Fig. 8.27 illustrates an AAA for two fault detectors, four steps of power measurement and four actuating elements.

Dots indicate points where patchtips are plugged in.

Referring to the diagram, the cross-connecting board performs the function of a storage device storing in a certain form the results of previously made calculations.

Fitting diodes at the joints between the input and output busbars form devices called *Diode Matrix Units* (DMU). These not only store information, but also perform a set of operations, type AND and OR, in the same way as relay-AAA does. This analogy is evident from the diagram shown in Fig. 8.28. In this case input pulses are fed by breaking rather than making the contacts, a voltage appearing on an output bar, only when the circuits of all input bars connected to it are open.

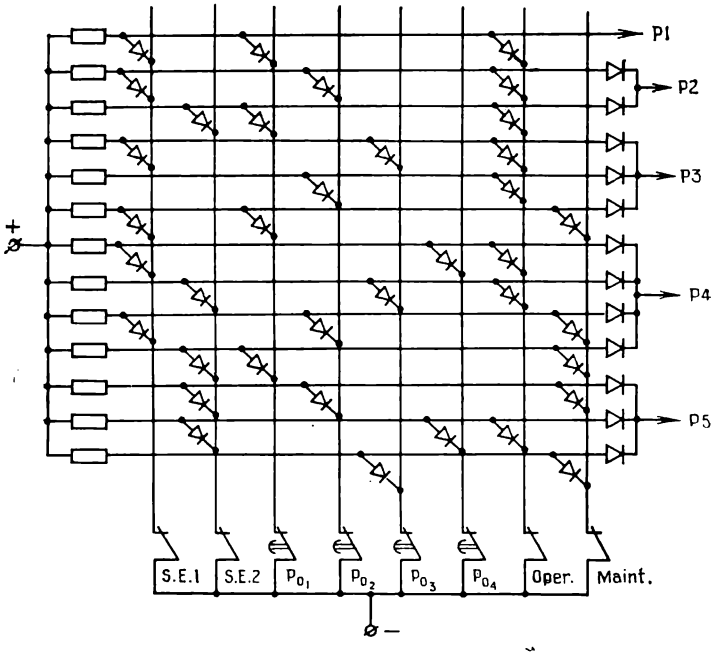


Fig. 8.28

AAAs utilizing relay-switching networks and DMUs are suitable only for small and medium-regions. With large controllable regions not infrequent in modern power systems use is expected of AAAs with a digital computer which may either control the switching operations of the device, or directly respond to the signals from the fault detectors by sending corresponding control commands.

Let such a structure be considered in more detail. For definiteness, assume that customized is an AAA version in which to make the automatic control gear immune to noise, the computer operates only under pre-fault conditions to process the above problem of control signal passing from fault detector to actuators. In this, use is made of the following algorithm: with the pre-emergency conditions of the system (its mode and configuration) known, the digital computer is given a certain number of fault detector N_i and defines what an effect on the system will be, if this element functions. The results obtained are then transferred to the switching device. This done, the above operation is repeated for fault detector number N_{i+1}.

A preliminary preparation of control actions like this simplifies the performance requirements for the digital computer in the moment of fault. Since the power system configuration and operating conditions change, but slowly, a cyclic algorithm with a 20-s cycle will

suit well. This time is enough to compute steady-state relations for each event, while actions to control the process dynamics should be searched on the basis of data obtained by preliminary computations with the aid of more powerful facilities. In this a problem of data storage arises. Neglecting the possibility of inserting various corrections and utilizing similarity criteria (empirical or analytical and the like), we may indicate only two essential methods of such storage. These are:

(a) Data representation in the form of the so-called "decision tables" which means specifying needed relations in a table form;

(b) Data representation through analytical function approximation with storing all their associated constants and executing appropriate computations, as the necessity arises.

In order to define the amount of information to be stored in the computer memory in each of these cases digitize S_0, having replaced all its possible values by the finite set of vectors S_{0j}, $j = 1, 2, \ldots$ $\ldots, l$. Then, with N_i and S_{0j} assumed to be points of approximation, replace $U(V, S_0)$ by a piecewise-constant (stepwise) function drawn so that the resultant intensity of action is not anywhere less than its sufficient value and greater than its permissible value. If that is the case, a set of control vectors is formed which may be represented in the form of a rectangular matrix

$$M = |U_{ij}| \tag{8.36}$$

size $n \times l$, n being much less than l, and the matrix is sparse which may be used to compress the information. By definition one of the columns of this matrix corresponding to the current operating conditions of the system should be always stored in the computer memory, or in the switching device, while the others may be stored either as such, or in the form of constants necessary for their computation.

In order to define the amount of information that is to be stored in either case break up the vector S_0 into two vectors:

$$S_0 = S_0' \cdot S_0'' \tag{8.37}$$

one of which depicts the system parameters and the other, system state variables. Denote h' and h'' as dimensions of vectors S' and S'', respectively; $\hat{S}_k'$ and $\hat{S}_m''$ as number of digits (the logarithm of the number of discernible states to the base of "2") for each of h′ and h″ dimensions. In this

$$l = 2^{\sum_{k=1}^{h'} \hat{s}_k' + \sum_{m=1}^{h''} \hat{s}_m''} \tag{8.38}$$

Let the number of constants to approximate the required relations for each of h'' dimensions be ξ and denote the number of digits in each of these constants as $\hat{\xi}_{\xi}$. The length of the control code is deter-

mined by the number of the separate actions carried out by the automatic control gear and by number μ of discernible states in the execution of each of the actions is then denoted as $\hat{u}$. It is evident, that in order to store the column of control actions corresponding to the current state of the system S_{0j} we need the following storage space (in bytes):

$$C_0 = \frac{1}{8} k_c n \hat{u} \tag{8.39}$$

where k_c is the data compression factor accounting for the possible use, when certain fault detector operates only of null control actions.

If all information needed to form this column is stored in the table form (T), then the number C_0 must be multiplied by the number of combinations (zones) of state variables:

$$C_{1T} = 2^{\sum_{m=1}^{h''} \hat{S}_m} \tag{8.40}$$

and then by the number of combinations (zones) of system parameters:

$$C_2 = 2^{\sum_{k=1}^{h'} \hat{S}_k} \tag{8.41}$$

The total amount of information in storage (without subscripts and pointers) then will be (in bytes):

$$C_{\Sigma T} = \frac{1}{8} k_c n \hat{u} \cdot 2^{\sum_{k=1}^{h'} \hat{\mathbf{S}}'_k + \sum_{m=1}^{h''} \hat{S}''_k} \tag{8.42}$$

If the association of control action with state variables is stored in the form of constants (an approximating function a), the required storage space is (in bytes):

$$C_{1a} = \sum_n \sum_{q=1}^{\xi} \hat{\xi}_q \tag{8.43}$$

the number C_2 remaining as before. Hence, the overall amount of information in that will be

$$C_{\Sigma a} = \frac{1}{8} \sum_n \sum_{q=1}^{\xi} \hat{\xi}_q \tag{8.44}$$

and the relationship

$$\frac{C_{\Sigma T}}{C_{\Sigma a}} = \frac{r_c n \hat{u} \cdot 2^{\sum_{m=1}^{h''} \hat{S}''_k + \sum_{k=1}^{h'} \hat{S}'_k}}{\sum_n \sum_{q=1}^{\xi} \hat{\xi}_q} \tag{8.45}$$

It is apparent that to store all the required information in the form of constants requires less storage space than its storage in the form of tables of decisions. The former form however has disadvantages in that it calls for a greater amount of preliminary calculations and is less clear. On the other hand, the capacity of storage devices of modern computer is ever increasing, and zones of system variables may be stored on magnetic disks and system parameters on magnetic tape. Therefore, both versions of storage may compete with each other.

Possible methods of control. Despite the wide application of preset (programm) emergency control devices, efforts are made at present to develop and put into practice emergency control devices operating on other principles of operation, the results of which are still at the stage of laboratory and industrial experiments. This research work is because of disadvantages inherent in the preset control technique. Thus, for instance, one of its disadvantages is in that it provides, but very little possibility of taking into consideration under emergency conditions various combinations of continuously varying quantities. Sometimes comparing power on individual transmission lines, frequencies in different parts of a power pool, etc. is helpful in recognizing an arising emergency situation. This is not easy with the use of traditional forms of preset control based on relay fault detectors.

Therefore, new devices are under development that provide for processing of all information available, including continuous information coming in directly under emergency conditions. In this, like the case is with the preset control, control commands are produced through the use of preset relations which herein are processed in the analog form providing for in this case the required speed of response and somewhat better possibilities. Thus, for instance, it is easy to make the operation of the device under short-circuit conditions dependent not only on P_0, but also on ΔP_{sc} (in compliance with the expression (8.32)). To go over from one characteristic to another use is made of nonlinear networks with multiplying-digital-to-analog converters (MDAC).

One element utilizing a MDAC is shown in Fig. 8.29*a*. Changing digital codes fed to the MDAC under any emergency conditions, characteristics with different slope and cutoff can be reproduced (Fig. 8.29*b*).

The above mentioned device somewhat improves the capabilities of the preset control, eliminating limitations inherent in the operating principles of the fault detector. It, however, does not rule out the principal disadvantage of the preset control technique—its unsuitability for handling infrequent, but fairly dangerous to power system cases in which faults are imposed on each other.

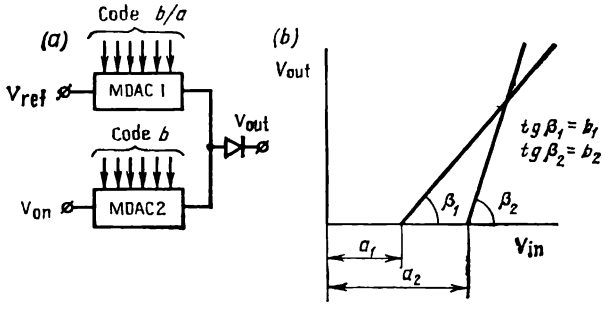


Fig. 8.29

In fact, control actions designed for certain pre-fault conditions assumed as steady-state become unsuitable for the purpose, when these conditions turn out to be transient because of a preceding fault. More than that, since the time interval between the first and second faults is random, good results cannot be obtained whatever perfect may be the principles of preset control. In view of this such devices are unabled for 3-5 s after the first fault, using the back-up control gear (sectioning devices, for example) to cope with the second fault.

There are two ways of modifying the devices in question. One consists in wide application of asynchronous operation periods one, two, or three cycles in duration, which forms a reserve of time for the performance of control devices that continuously monitor the system operating conditions (like conventional governors). If that is the case, provision is made for use of high-speed resynchronizers in addition to low-speed ones which are now utilized though in small numbers.

The other way comes to use of a fast prediction made capable of operation in faster-than-real time which makes it possible to choose required control actions directly during the course of a fault regardless of its flow.

The operating principle of such a predictor can be well explained using the choice of a control pulse for the emergency control of steam turbines as an example. Let all information typical of transient processes in a power system (δ, s and ds/dt, or P_0 and ΔP_{sc}) be sent to this device, while the device incorporates a high-speed model of a power system and a turbine on which processes can be calculated, the duration of pulse T_p being gradually increased until it is enough to sustain transient stability. Then, the result obtained is transferred to the device governing an actual turbine, while the predicting device continues the process monitoring producing, as necessary,

commands to increase the pulse duration, perform sectioning of the system, etc.

In experiments a model of the device was operated at a speed 100 times the real time and, if a disturbance was of single action, it defined the instant of stopping a pulse that had been fed to the turbine within 5-7 computation operations taking in total less than 0.1 s. It is thus apparent that, if available, such a high-speed and dependable device would find its applications in the emergency control technology to tackle most diverse problems, including the above-mentioned problems of preset control.

And what is of interest, the above-discussed principle could be readily customized today in the form of a hybrid computer system comprising an analog model for the predicting purposes and a digital computer to serve this model and at the same time utilized as a machine to accomplish the preset control.

Modern analog computer technology allows the above-mentioned prediction to be performed at speeds 1000 times the real time, while the use of digital computers and multiplying digital-to-analog converters (MDAC) makes it possible to enter into the utilized model all changes connected with variations in the configuration of a power network, its operating conditions, etc.

Emergency control and ADCS. The emergency control facilities form one of the undispensable parts of the automatic dispatching control system (ADCS).

Transient processes occurring at faults in power systems are system-wide, and notions of managing these transients from a common centre with the use of powerful computer facilities were put forward far before the appearance of ADCS. With the progress of ADCS these ideas become more and more urgent. For their complete realization not only appropriate control centres must be furnished with digital computers, but practical experience should prove reliability and noise immunity of this scheme.

Stringent performance requirements are also placed on the communication channels and on the other equipment of the system utilized to transfer data to the control centre and send commands to the controlled units.

The emergency control schemes are dovetailed with other components of ADCS in several stages.

First considered are the capabilities of the control schemes to expand the area of pre-fault conditions S_0 used. As is known this area must belong to a certain permissible area S_{op}. More than that, in addition to common restrictions determined by voltage levels, lines, load flows and the like, mode restriction caused by S_{2l} by which is meant the choice of such pre-fault operating conditions under which the system can be held within the permissible area S_{2p}, or returned to this area along a permissible path at any fault

foreseen in the planning. To satisfy this requirement, especially on large power utilities, the emergency control technology has much to do, as is known.

In planning operating conditions of power system the performance of the emergency control schemes must be taken into cosideration, but this may be accomplished in different ways. A most simple way is to specify the utmost loads carried by the transmission lines and other state variables in the pre-fault conditions based on previous calculations of similar and close conditions. This method however may be recognized only as approximate, inasmuch as in stability calculations, restrictions on one variable (say the load flow over one transmission line) are much more dependent on the set of other variables (loads of the other transmission lines, voltages, and the like).

This is what differs stability constraints from say current restraints in which case utmost values of variables being limited can be specified at once and with high degree of approximation taken into account directly in the optimization calculations with no special model studies which will materially facilitate the calculation procedure and simplify requirements for the equipment.

Different matter is in the analysis of stability constraints, especially with regard to the effect of emergency control. In this case model studies are needed to fully take into consideration all contingencies that may arise. If that is the case, the general algorithm of planning operating conditions is an extended usual algorithm of planning operating conditions of a power system (Fig. 8.30).

Referring to Fig. 8.30, it follows that after the operating conditions have been optimized with taking into account current constraints, the conditions are simulated under the effect of the entire set of disturbances V. If in that $S_2 \subset S_{2p}$, the operating conditions are acceptable and can be put into practice. If $S_2 \not\subset S_{2p}$, attempts must be made to select proper actions and settings of emergency control schemes with a view to satisfying this condition.

With all possibilities in this respect exhausted, the planned S_0 must be altered for the good of improved reliability.

The algorithm is realized now in interactive mode with a human searching for the emergency control facilities and settings, and changing, if necessary, the constraints taken into account in the course of optimization calculations. It is proposed to accomplish this operation in future automatically. And what is more, referring to the flow chart in Fig. 8.30, the associated units have a by-product-output data related directly to the emergency control.

With emergency control taken into account, not only the so-called typical operating conditions may be analyzed, but all operating conditions that are to be realized. This however calls for very large

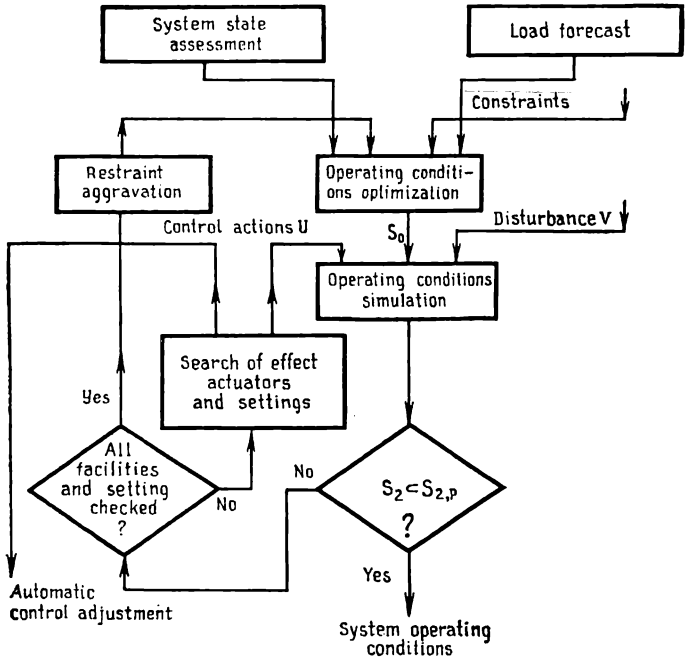


Fig. 8.30

computer, requirements for which turn out the more stringent, the smaller the time reserved is left for computations.

Of importance is the problem of real time stability of improvement that is similar to that of economic dispatch but in addition to the control of the stations the former calls for corrections also on the settings of emergency control. This problem turns out to be fairly complicated. Even in a simplified formulation (i.e. with the emergency control not included), although with large computer facilities available, its solution first seemed possible, only with use of decision tables. It follows from the above-mentioned relations that the amount of information contained in such tables (and ADCS must provide, for storage of information simultaneously about a great number of power utilities) would be very large. In view of this hybrid computer systems including faster-than-real time computers find ever more applications.

The incorporation of the automatic emergency control into ADCS leads therefore to certain complication of the equipment required. At the same time, the equipment of emergency control itself can be simplified. Thus with the present control emergency system the

automatic devices adjusting paths for signals fed from the fault detectors to the actuating elements may be replaced by remote adjustments in response to the appropriate signals from the control centre machines. The same machines detectors may be used to change the settings of fault detectors in order to take into account specific features of given actual operating conditions of the power system. Even direct digital or hybrid remote control of the main equipment under emergency conditions is feasible on the basis of the centralized control.

Customizing all these capabilities in practice will depend on the reliability of the equipment, first of all on the communication channels.

In fact, with ADCS created, the control centres of the power systems collect practically all information required for the emergency control (except for, perhaps, such signals as ΔP_{sc} and the like). There are also special channels of remote control which may be utilized say to adjust the passage of signals to the EPA. The overall reliability, however, and sometimes the operating speed of such channels are sometimes low. In view of this, the emergency control devices are installed at the present stage preferably at large power stations or substations sited in the centres of the grid, information being transferred to them with the aid of highly reliable equipment made for the purpose.

Suggestions have been made on centralized emergency control devices appended by computers. These devices should cover large areas (emergency control areas), the most perfect places of siting the centres of these areas being not coincident with the siting places of the control centres. The boundaries of the territories covered by these areas may differ from the power pool boundaries adopted at present. Therefore, being part of ADCS the emergency control may sometimes be based on its own equipment as somewhat independent.

Review Questions

1. What is the purpose of the automatic emergency control of modern power systems? What is the difference between the emergency control and ordinary operation control of power systems?
2. What basic emergencies are probable in one- and two-equivalent power systems and ring system?
3. What are the basic effects of emergency control on the operating conditions of a power system? Which effects are preferred at hydro electric plants and at thermal power plants?
4. What are the specific features of using GR in one- and two-machine equivalent power systems? What is the efficiency of this measure in these power systems?
5. Describe the phenomenon of a power surge on a power transmission line. What electromechanical transients occur during this phenomenon? What static relations are characteristic of it?

6. When is the use made of out-of-step protection? What is necessary to resynchronize power systems after these measures are carried out?
7. How are the single-action and multi-action braking controlled? What is the key difference between these two types of braking?
8. How is the post-emergency power limitation organized after FTC? What is the difference between EPLs for mechanical and electrical power?
9. How does an AAA operate? How is the number of data storing contacts in it calculated?
10. How is a storage space for emergency control settings data determined?

Bibliography

1. Venikov V. A., Idelchik V. I. *Advances in Science and Technology*: Electric Stations, Networks and Power Systems. Vol. 7. Methods of Optimization of Large Power System Management and Control (Optimization of Power System Expansion and Operation). Moscow, VINITI, 1974 (in Russian).

2. Venikov G. V., Stroev V. A. *Computational Methods of Investigations into Power Systems* (Ed. by V. A. Venikov). Moscow, "Energiya", 1973 (in Russian).

3. Kagan B. M., Kanevsky M. M. *Digital Computers and Computer Systems* (Ed. by B. M. Kagan). Moscow, "Energiya", 1974 (in Russian).

4. Krumm L. A. *Methods of Reduced Gradient to Control Power Systems.* Novosibirsk, "Nauka", 1977 (in Russian).

5. Luginsky Ya. N., Semenov V. A. *Information-Computation Systems in Dispatch Control.* Moscow, "Energiya", 1975 (in Russian).

6. Melentyev L. A. *Optimization of Large Power System Expansion and Operation.* Moscow, "Vysshaya Shkola", 1976 (in Russian).

7. Portnoy M. G., Rabinovich R. S. *Power System Stability*: Control Problem. Moscow, "Energiya", 1978 (in Russian).

8. Pospelov G. E., Kernogo V. V. *Management Control Systems and Optimization of Power System Operating Conditions.* Minsk, "Vysshaya Shkola", 1977 (in Russian).

9. Rudenko Yu. N., Cheltsov M. B. *Reliability and Duplication in Power Systems.* Novosibirsk, "Nauka", 1974, (in Russian).

10. Venikov V. A., Gorushkin V. I., Markovich I. M. et al. (Ed. by V. A. Venikov). *Electric Power Systems*: Computations, Programming and Optimization. Moscow, "Vysshaya Shkola", 1973 (in Russian).

11. Astakhov Yu. N., Venikov V. A., Gorsky Yu. M., Karasev D. D., Markovich I. M. *Electric Power Systems*: Cybernetics in Electric Power Systems (Ed. by V. A. Venikov). Moscow, "Vysshaya Shkola", 1974 (in Russian).

INDEX

Addressing,
  direct, 333
  indirect, 333
Amplifier,
  operational, 255, 261
Analyzer,
  network, 254
Annunciator,
  light, 114
Area, 70
Arithmetics,
  binary-coded-decimal, 323
Attachment,
  electric, 83
Automatic control,
  in power systems, 23
Automation, 22

Balance,
  energy, 12
  water, 26
Ball,
  tracking, 133, 145
Banks,
  condenser, 100
Bit, 317
Board,
  area-level control, 116
  display, system diagram, 114, 124
  projection-type, 114
  regional control, 116
Box,
  black, 39
  grey, 48
Braking,
  electrical (electrodynamic), 369, 389
  multi-action, 391
  single-action, 391
Bus,
  slack, 73
Byte, 317

Changer,
  speed, 63
Changing,
  on-load tap, 100
Channels,
  communication, 192
    non-switched, 193
    switched, 193
Chroma, 127, 128
Chromaticness, 127
Code,
  binary, 317
  parallel, 317
  serial, 317
Color, 127
Comparator, 268
Compensator,
  synchronous, 100
Complex,
  computer, 111, 160
  fuel-and-energy, 12
Computers,
  analog, 253, 279
  business-oriented, 309
  hybrid, 253, 259, 279
  scientific, 310
Conditions,
  emergency, 21
  operating, 21
  out-of-step, 24
Configuration, 21

Controller,
frequency, 190
Converter,
analog-to-digital, 208, 259, 276
digital-to-analog, 259, 276
frequency, 190
Costs,
fuel, 72
Cyberneticists,
power system, 9
Cybernetics,
power system, 39

Decoder, 331
Demodulator, 195
Department,
Central Control, 116
Desk,
control, 152
Deviation,
frequency, 22
voltage, 22
Devices,
telecontrol, 203
Diagram,
wall (mimic), 114, 124, 150
dark, 151
Dispatch,
economic, 59
Distance,
standard observation, 128, 129
Drift,
amplifier, 264

ENERGIYA branch-wise management control system, 104
Equipment,
multiplexing, 194
pulse-code modulation, 192
sub-multiplexing, 196
Facilities,
data display, 124
active, 124
group-use, 114, 124
individual, 114, 124
passive, 125
Filters,
electrostatic, 26
dust, 26
Flows,
power,
fixed program, 65
nonfixed program, 65

Generator,
character, 141
function, 270
vector, 142
Governor,
speed, 83

Hammer,
water, 79
Hierarchical structure (power system dispatch control), 116, 118
Hue, 127, 128
Hydroturbines, 76

Identifier, 355
Illuminance (illumination), 127
Image contrast, 126
Immunity,
noise, 201
Indicators,
analog, 115
CRT, 130
digital, 115
Interrupts, 345

Job, 352
Joystick, 133, 146

Key, 355

Links,
communication,
buried (cable), 193
overhead, 193
power-line carrier, 203
Luminance (photometric brightness), 126
Logic,
combinational, 323

Memory,
main, 332
read-only, 331
Meshkov interlocking facility, 362
Method of mathematical analogs, 253
Microoperation, 326
Microprocessor, 359
Mini-computers, 357
Mix,
generating, 21

Mode,
dead band, 98
duplex, 213
emergency assistance, 98
half-duplex, 98
normal control, 98
simplex, 213
Model,
computing, 254
indirect-analogy, 254
Modelling,
cybernetic, 38, 39
mathematical, 39
physical, 38
Modem, 226
Modulator, 196
Multiplier, 270
Multiprogramming, 313
with a fixed number of tasks, 356
with a variable number of tasks, 356

Networks,
distribution, 21, 100
subtransmission, 21, 100
Null detector, see Comparator

Offset,
frequency, 63
Operating system, 313
Outages,
planned, 120
unplanned, 120

Pattern recognition, 128
Pen,
electronic, 147
light, 147
Period,
sampling, 204
Persistence, 134
Phosphor, 134
Plotter,
graph, 125
X-Y, 115
Pollution,
thermal, 26
Pollution control, 17
Pool,
power, 71
Power supply,
emergency, 157
Power system, 18
Printer,
alphanumeric, 115

Processor,
display, 133, 136
Program,
primary control, 356
Protection,
out-of-step, 367

Rate,
fuel, 72
sampling, 204
Regulation,
primary, 58, 75
secondary, 59, 87
speed, 62
tertiary, 59, 89
Repeater, 193
Requirements,
floor and volume space, 18
Reserves,
actual, 15
probable, 15
projected, 15
Resources,
nonrenewable, 15
renewable, 15
Room,
control, 154, 157

Scheduler,
load, 59
Schemes,
closed-cycle water-cooled, 26
emergency control, 23
transmission, 223
Section (in steam turbine),
high-pressure, 80
low-pressure, 80
medium-pressure, 80
Shielding,
radiation, 26
Speed,
computer, 335
data output, 126
transmission, 214
Stability,
resultant, 64
steady-state, 371
transient, 64, 371
Stack, 334
Stations,
pumped-storage, 19
terminal, 193
transmit-receive, 193
Substations, 21

Superheater,
intermediate, 81
Super-pool, 71
Supervisor, 353
System,
coal supply, united, 28
coding, 129
data transmission, 223
dispatch control, automated, 58
gas supply, united, 28
hydraulic turbine governing, 58
oil supply, united, 28
pan-energy, national, 28
power system dispatch control, 56
real-time computer, 111, 160
speed-responsive governing, 58

Tariffs, 44
Telecommand, 205
Teleindication, 205
Telemetering, 205
Teleregulation, 205
Terminal,
final, 193
Tie lines,
intersystem, 21
Time sharing, 315
Transfers,
inter-area, 60
Transmission,
suppressed-carrier single-sideband, 195

Unit,
central processing, 322
character-mode (alphameric), 131
CRT display, 114, 130
graphic, 131
pseudographic, 142
United Power Grid, 11, 28, 116

Valves,
interceptor, 81
Variables,
state, 21
system, 21

Work orders (plant maintenance), 121

To the Reader

Mir Publishers welcome your comments on the content, translation, and design of the book.

We would also be pleased to receive any suggestions you care to make about our future publications.

Our address is:
USSR, 129820,
Moscow, I-110, GSP,
Pervy Rizhsky Pereulok, 2,
Mir Publishers

Printed in the Union of Soviet Socialist Republics

Other Books from MIR Publishers

(Construction of Nuclear Power Stations)

V. Dubrovsky, D. Sc. (Editor)

This is a systematic presentation of material covering the civil-engineering side of nuclear power station projects. A brief outline is given of nuclear reactors and basic accessories. A more detailed discussion is devoted to the choice of sites, environmental safety, and station layouts. Data are given on the materials and structures used for biological shielding. The book is intended for nuclear power station designers, builders and operators, but may also be useful to students majoring in nuclear power station construction.

Contents. Nuclear Reactors and Basic Accessories. Siting. Station Layout Planning, Scale. Modelling. Elements of Station Buildings and Structures. Biological Shielding. Methods of Construction.

Electrical Network Performance Calculations and Analysis

V. VENIKOV, D.Sc. (Editor)

This textbook, meant for the students of electric power engineering institutes, is a book of collected problems and examples of electrical network performance analysis and calculations. All the examples are supplemented with detailed solutions, illustrating curves, tables, and explanations that will assist in a more comprehensive understanding of the theory of respective subjects. This characteristic feature peculiar to the present book distinguishes it from ordinary books of problems and allows it to be characterised as a textbook of a new type.

Nuclear Power Stations

T. Margulova, D. Sc.

The author of the textbook Prof. T. Margulova is a well-known specialist in the field of heat-and-power engineering. The book explains the theory of thermal electrical power stations as applied to power plants using nuclear fuel. It covers general problems for any thermal electric power station (conventional and nuclear) and specific ones which are true for nuclear power plants only. The textbook is for university students and may be used by engineers specializing in design start-up and operation of nuclear power stations.

Contents. Introduction. Electric and Thermal Power Distribution and Consumption. Types of Nuclear Power Stations (NPS) and Their Basic Technological Equipment. Physical and Chemical Processes in NPS Thermal Systems. APS Thermal and Total Efficiency. Regenerative Feed-Water Heating. Feed-Water Deaerators. Condensers. Water Supply Systems. Vapourizers and Combined Heat-and-Power Supply Systems. Reactors. Steam Generators. Turbines. Regulators and Pipe-Lines. NPS General Layout. Ventilation System. Deactivating Installations. NPS Organization and Operation. NPS Thermal Systems and Methods of Their Calculations. Layout of NPS Main Building with Water Coolant System. NPS with Gas and Liquid-Metal Coolant Systems.

Transient Phenomena in Electrical Power Systems

V. VENIKOV, D.Sc.

470 pp. 17×26.5 cm. Cloth.

A textbook for university students in power and electrical engineering faculties; will be useful to engineers and technicians concerned with the design and operation of various electrical systems, circuits and power networks, and installations for the generation or conversion of electricity. Translated from the second, fully revised and supplemented Russian edition.

About the Editor. Honoured Scientist and Engineer of the RSFSR, Doctor of Sciences, Honorary Doctor of the Dresden University, Professor Valentin Andreevich Venikov was born in 1912 in Nizhni Novgorod (now Gorky). He graduated from the Moscow Power Engineering Institute in 1935 and received the Candidate (Ph.D.) degree in 1940, the D.Sc. degree and the title of Professor in 1953.

Professor V. A. Venikov is the author of fundamental works in the field of physical simulation, stability and application of cybernetic methods for electric power system analysis and synthesis. He enjoys wide popularity both among the USSR and foreign engineers and scientists as enterprising organizer of new and perspective investigations.

At present he heads the department of Electrical Systems and is the research supervisor in the laboratory of Electrical Systems at the Moscow Power Engineering Institute.

The department headed by Professor V. A. Venikov has become the school of thought not only for future scientists, but also for skilled specialists. Under his guidance, more than 100 theses for Candidate and Doctor's degree have been successfully completed. He has prepared original lecture courses in "Transient Phenomena in Electrical Power Systems", "Theory of Similarity and Simulation with Application to Problems", "Cybernetics in Electrical Power Systems", "Cybernetics and Automatic Control in Electrical Power Systems", etc.

He is the author of about 400 scientific publications including 25 fundamental books. He has to his credit 30 inventions. At his initiative and with his participation, an eight-volume book on "Electrical Power Systems" has been written, which covers the main problems of this field of science. Books of Prof. Venikov have been translated into seven languages: English, Spanish, Bulgarian, Rumanian, Czech, Chinese and Japanese.

In 1958, Professor Venikov was awarded the Lenin Prize for the development of electrodynamic models for practical investigations of large power systems, long distance power transmission lines and equipment of power stations.

The scientific, educational, and public activities of Prof. Venikov has also been highly appreciated. He has been awarded the Order of Lenin, three Orders of Honour, and Medals.

Recently he has been awarded a State Prize, for the book "Transient Processes in Electrical Power Systems".